AMC PAMPHLET AMCP 706-107

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RESEARCH AND DEVELOPMENT OF MATERIEL

ENGINEERING DESIGN HANDBOOK

ELEMENTS OF ARMAMENT ENGINEERING
PART TWO
BALLISTICS

EADQUARTERS, U. S. ARMY MATERIEL COMMAND SEPTEMBER 1963

HEADQUARTERS
UNITED STATES ARMY MATERIEL COMMAND
WASHINGTON 25, D.C.

30 September 1963

AMCP 706-107, Elements of Armament Engineering, Part Two, Ballistics, forming part of the Army Materiel Command Engineering Design Handbook Series, is published for the information and guidance of all concerned.

(AMCRD)

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ELEMENTS OF ARMAMENT ENGINEERING

PART 2, BALLISTICS

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PREFACE

The science of ballistics involves the study of the motion of projectiles as a particular branch of applied mechanics and related fields of physics, chemistry, mathematics, and engineering. It includes, within its scope, the natural division of this science into the subjects of interior ballistics, the motion of a projectile or missile while under the influence of a gun or thrust propulsion device; exterior ballistics, the projectile or missile in flight; and terminal ballistics, its effectiveness in defeating a target. With each successive performance dependent on that preceding, the overall ballistic performance of any missile or projectile must consist of reliable and reproducible actions in each of these phases despite conflicting design requirements in certain areas.

Ballistics produces a rational foundation for the design and development of armament materiel. Therefore, a concept of the basis for the design of weapons or development of ammunition cannot be realized without a basic understanding of this science. The following chapters present information about each phase of ballistics to the extent believed necessary to pursue a study of the design and engineering analysis of components of weapon systems which satisfy the basic requirements of launch, flight, and terminal effects. Such problems are presented in Part 3 (Weapon Systems and Components) of this text.

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CHAPTER 1

INTERIOR BALLISTICS—GUN PROPULSION SYSTEMS

1-1 INTRODUCTION

Prior to the fourteenth century military life was not complicated by the study of interior ballistics. Missiles could be projected by muscle power, slings, catapults, or by elastic forces applied through bows, crossbows, and ballistas. In 1346, the English, by using gun-launched projectiles against the French, gave birth to interior ballistic phenomena. Since that time, the design of cannon has progressed from the old cast iron and bronze tubes to the modern high quality steel guns with rifled bores. With this advance has come the requirement for projecting larger missiles at ever increasing velocities and to greater ranges by varied systems of propulsion.

The projection of missiles at the high velocities and other conditions demanded today, requires tremendous force. The source of the energy which supplies these forces must be readily manufactured, easy to transport, and capable of being safely applied. At various times, proposals have been made for utilization of energy provided by means other than explosives such as compressed air, electromagnetic force, and centrifugal force. Thus far, however, no results have been attained from any of these sources which approach those realized from chemical explosives.

Interior ballistics (that branch of ballistics dealing with motion imparted to a missile) comprises a study of a chemical energy source, a working substance, and the accessory apparatus for controlling the release of energy and for directing the activity of the working substance. Of allied interest is the mechanical functioning of guns and accessories.

Since unnecessary weight is an unjustified logistical extravagance, weapons are designed to operate under greater extremes of temperature and pressure than are usually encountered in the use of non-military engines. Because the time cycle involved is quite small, there is not sufficient time for the consummation of slow processes such as heat transfer. Consequently it is necessary that the chemical energy source must also furnish the gaseous products which in themselves constitute the working substance. This energy source may be a solid propellant as in most guns, or a liquid fuel and oxidizer source such as is currently used in rocket propulsion.

As previously described in this text, propellants are studied from several aspects. Thermodynamic properties indicate the release of as much energy per unit weight as may be consistent with other demands. Studies of the mechanism of decomposition indicate the effects of uncontrollable parameters such as ambient temperature. Dynamics of the gases are necessarily a subject of investigation because the kinetic energy of the propelling gases is an important part of the total energy of the process. The study of motion of a projectile inside the gun tube is not a matter of simply applying Newton's laws to the motion of the projectile regarded as a point mass, but a complicated study of the rate at which the high temperature gas is evolved from the propellant; the motion of the gas so produced; and the effect of this gas on the motion of the projectile itself. The passage of the solid projectile stresses the tube mechanically and subjects the interior of the barrel to sliding friction. The passage of high temperature gases, in addition to the high pressures generated, heats the barrel to the extent that chemical interaction with the metal itself occurs.

1-2 ACTION INSIDE THE GUN

A modern gun or mortar is essentially a heat engine. Its action resembles the power stroke of an automobile engine with the expansion of hot gases driving the projectile instead of a piston (Figure 1-1). When the charge is ignited, gases are evolved from the surface of each grain of propellant and the pressure in the chamber increases rapidly. Resistance to initial motion of the projectile is great, and is largely due to its inertia, its friction, and the resistance of the rotating band to engraving. The projectile normally does not begin to move until the pressure reaches values ranging from 6000 to 10,000 psi.

The chamber volume is increased, which has the effect of decreasing the pressure; however, the rate of burning of the charge increases. The net effect is a rapid increase in the propellant pressure until the point of maximum pressure is reached. This occurs at a relatively short distance from the origin of rifling. Beyond that point, pressure drops and, at the muzzle, reaches a value considerably less than maximum pressure, probably of the order of 10 to 30% depending upon the weapon design. This muzzle pressure continues to act on the projectile for a slight distance beyond the muzzle. Thus, the projectile continues to accelerate beyond the muzzle.

A special form of this method of propulsion is represented by the recoilless system (Figure 1-2). Here controlled burning of additional propellant permits discharge of gases through a nozzle at the breech. The rate of discharge of gases can be controlled by controlling propellant burning, thus permitting a balance of the momentum of the gun-propellant gas-projectile system. The interior ballistic problem here is not only one of combustion but of balancing the orifice diameter against thrust required to maintain a mean velocity of the weapon at zero. The propellant weight in this case exceeds that for a comparable cannon by a factor of 2 to 3. The pressure-travel curve is designed for minimum muzzle velocity consistent with accurate exterior ballistic performance, thus permitting the use of a thin gun tube which is necessary to maintain the characteristic light weight of this weapon.

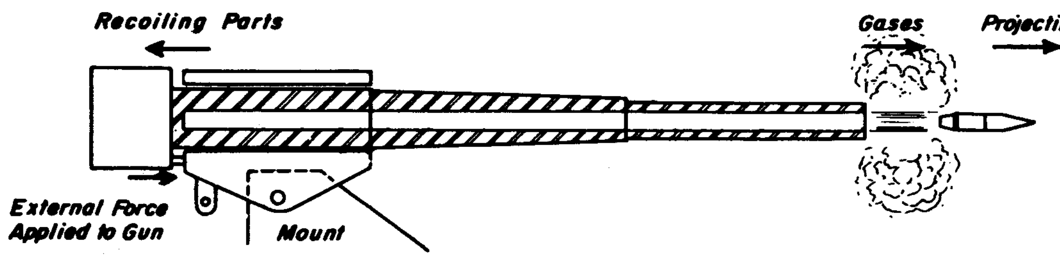


Fig. 1-1 Standard gun system.

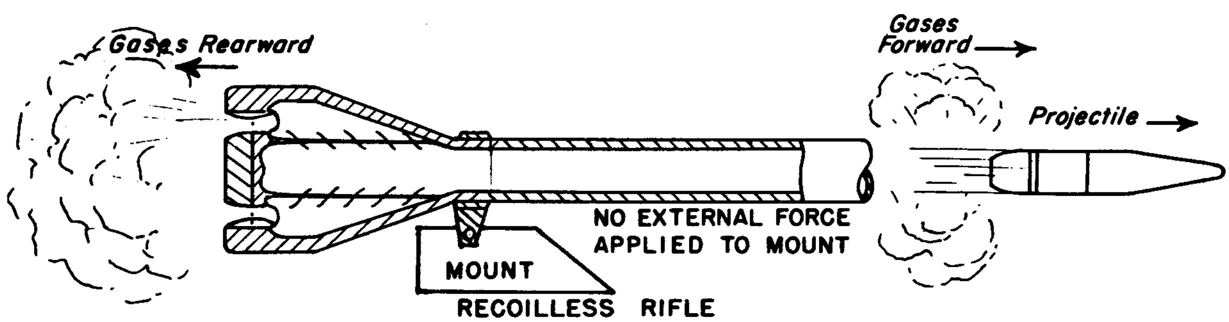


Fig. 1-2 Recoilless system.

1-3 DISTRIBUTION OF ENERGY

The energy developed by the burning of the propellant in a medium caliber gun, assuming complete combustion, may be distributed as follows:

Energy Absorbed	% of Total	
Translation of projectile	32.00	Reflects in the area generated under a pressure-travel curve for the cannon, (Figure 1-3) (34.31%).
Rotation of projectile	00.14	
Frictional work on projectile (Due to engraving of rotating bands, wall friction, and effects of increasing twist)	2.17	
Translation of recoiling parts	00.12	
Translation of propellent gases	3.14	
Heat loss to gun and projectile	20.17	
Sensible and latent heat losses in propellent gases	42.26	
Propellant potential (Q_v)	100.00	

1-4 PRESSURE—TRAVEL CURVES

In order that the projectile may leave the bore at the designated muzzle velocity, and that the pressures developed to accomplish this do not damage the weapon, all tubes are designed in accordance with a desirable pressure-travel curve for the proposed weapon.

The pressure-travel curves (Figure 1-3) indicate the pressure (or force if pressure is multiplied by the cross-sectional area of the bore) existing at the base of the projectile at any point of its motion. Hence, the area under any of the curves represents the work done on the projectile per unit cross-sectional area, by the expanding gases.

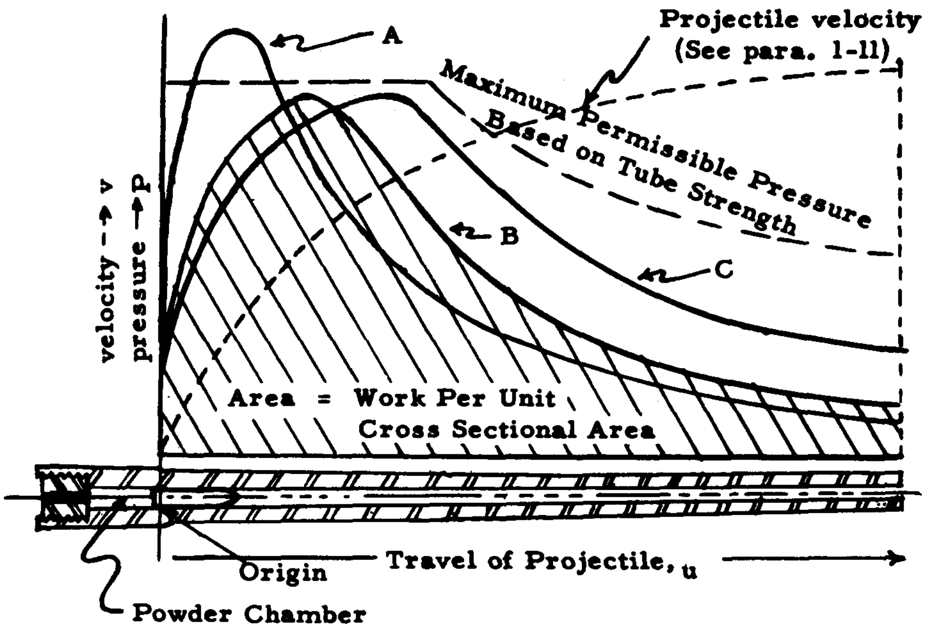


Fig. 1-3 Pressure-travel (solid lines) and velocity-travel (dotted lines) curves.

If the areas under curves A and B are equal, then the work performed in each of these cases will be equal, and the muzzle velocities produced by each of these powders will be the same, since

$$WORK = KE = \tfrac{1}{2} MV^2$$

The fact that curve A exceeds the permissible pressure curve cannot be tolerated.

Should it be desired to increase the muzzle velocity of a projectile, the work performed, or the area under some new curve, must be greater than the area under a curve giving a lower muzzle velocity. Such an increase in velocity is indicated by curve C whose maximum pressure is equal to that of curve B, but whose area is greater than that under B. It appears that the ideal pressure-travel curve would be one which would coincide with the curve of permissible pressure; however, if it were possible to design a propellant capable of producing such a result, many objectionable occurrences would take place. In addition to producing excessive erosion (a factor which would materially decrease the accuracy life of the gun), brilliant flashes and nonuniform velocities due to high muzzle pressure would result. Moreover, the powder chamber would have to be materially increased and this would affect the weight and hence the mobility of the gun. As a result of experience, the velocity prescribed for a particular gun is always somewhat below the maximum which it is possible to obtain; and the powder grain most suitable for producing this result is the one which will give the prescribed velocity uniformly from round-to-round without exceeding the permissible pressure at any point in the bore.

1-5 CONTROL OF INTERIOR BALLISTIC PERFORMANCE

Consideration of the desired relationships between gas pressure and projectile velocity necessary to meet the demands imposed for the achievement of desired ballistic performance, have been discussed in a general sense; however, it remains a fundamental problem of interior ballistics to determine and evaluate the influence of all variables of the problem. The solution may be based on theoretical analysis, established empirical relationships, or detailed, meticulous experimentation.

The variables basic to the problem include the following:

(a) Variation in chemical composition of the powder.

(b) Variations in rate of reaction.

(c) Variations in ignition characteristics.

(d) Variation in grain geometry (surface factors).

(e) Variation in charge weight (density of loading).

(f) Environmental factors.

The effect of chemical composition and the influence of pressure and temperature on combustion have been discussed. The influence of environmental factors must be considered (relative to design) in terms of the extent of their influence on gun performance.

1-6 IGNITION

In the ensuing discussions of the effects of grain design and charge weight, optimum ignition characteristics are presumed; however, the ignition problem has required extensive research, particularly in the design of ammunition for high velocity weapons.

Propellant powders must be ignited by high temperature and not shock, since the latter may cause detonation. This means that heat must flow from the hot primer flame to the powder grain. This sensible heat, plus that due to any adiabatic compression of gases in the vicinity, is the sole source of heat available to ignite the propellant uniformly.

Heat flow to the main charge is by two means: radiation and conduction. In the case where one body surrounds the other, the net radiation between them may be represented as

$$\frac{dq_r}{d\theta} = cEA\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right]$$

where

$\frac{dq_r}{d\theta}$ = rate of radiant heat flow
c = radiation coefficient, 0.172
E = emissivity or specific radiating ability
A = area of radiating surface
T_1, T_2 = absolute temperature of the radiating surfaces

Thus, radiant heat transmission varies with the area, and to the fourth power of the temperature of the radiating body. The emissivity E, of most solids is up to ten times as high as that of gases. For this reason, luminous flames which contain large numbers of solid particles in suspension in the flame radiate much more intensely than nonluminous flames. This accounts in large measure for the superiority of black powder for use in primers since the products of explosion contain large amounts of solids such as potassium carbonate and sulfate which radiate intense heat, in contrast to the nonluminous flames from smokeless powders.

Heat flow by direct conduction from a hot gas to a solid surface is described by:

$$\frac{dq_c}{dT} = kC_pAT_1^{0.25}\frac{(G)^{0.8}}{(D)^{0.2}}(T_1 - T_2)$$

where

k = conductivity coefficient
C_p = specific heat at constant pressure of the hot gas
A = area of the solid to which the heat is flowing
T_1 = absolute temperature of the hot gas
T_2 = absolute temperature of the cold surface
G = mass velocity of gas in contact with solid
D = average diameter of the solid

Thus the temperature, mass, and velocity of the gases generated are of prime importance; and when the hot gas is enhanced by the presence of incandescent solids, the radiation effects not only augment, but exceed those obtained by conduction.

Under ideal conditions, each grain of powder in the propelling charge would be ignited at the same instant by being brought into complete contact with the primer flame. The use of a large primer, as in large guns, requires so much black powder that the firing is not smokeless. Powder grains that are packed so closely together may so restrict the flow of hot primer flame that ignition may be irregular. From a purely theoretical viewpoint, the most satisfactory primer would consist of an explosive gas which would permeate the entire explosive charge and liberate solid particles (such as mixture of acetylene and oxygen producing carbon monoxide and incandescent carbon particles). The best practical solution remains black powder.

Originally, faulty ignition was a difficult problem in weapons employing long cartridge cases. The primer used was comparatively short, extending into the case only about one-quarter of its length. In order to remedy this unsafe and unsatisfactory condition, new primers were developed that were almost as long as the case itself. These long primers have almost eliminated the slow ignition problem and have reduced the amount of smoke and flash at the muzzle. No additional black powder is used but it is merely spread out over the longer length. In weapons firing separate-loading ammunition, imperfect ignition has been minimized by placing a core of black powder through each powder bag or by attaching an igniter to several parts of the charge.

1-7 EFFECTS OF POWDER GRAIN CHARACTERISTICS

Assuming proper ignition of all propellant grains, the characteristic shaping of pressure-travel or pressure-time relationships for the gun system, is dependent on such variables as grain composition (quickness), grain size, grain configuration, and density of loading. Although in a final design all factors may be involved, it is of basic importance to note first, the independent

effects of such variables.

Propellant compositions (single-base, double-base, nitroguanidine, etc.) were discussed in Part 1, as were definitions of configurations (degressive, neutral, and progressive burning propellants). Performance of gun systems is usually demonstrated using pressure *(P)*-travel *(u)* coordinates although pressure-time relationships are often used in experimental investigations.

In each case discussed in this paragraph, initial burning rates are directly related to area exposed for the total number of grains per charge; hence, it is difficult to consider the influence of single factors without making allowance for the total area initially exposed to kindling temperatures. For any pressure-travel curve, the shape of the curve is affected by the variables shown in Figure 1-4. For a given pressure-travel curve (Figure 1-4) the slope of the curve in the region (1) to (2) is dictated by ignition characteristics and total area initially exposed to burning: The region (3) to (4) will be governed primarily by the grain configuration.

1-7.1 GRAIN CONFIGURATION

Exposed burning area as a function of "percent grain consumed" (Figure 3-14, Part 1) offers a key to the effects of configuration on pressure-travel relationships. As indicated in Figure 1-5, changing configuration to a more progressive burning design (employing grains of the same initial surface area, composition, and total charge weight) results in lowered peak pressures (with peak pressure occurring later in the cycle) and in higher muzzle pressure when compared with degressive grains. For identical charge weight, areas under the curve are approximately equal. In order to meet requirements for equal initial surface areas for the total charge, the degressive grains must be the smallest of the designs considered.

1-7.2 GRAIN SIZE

For a fixed weight of charge of similar composition and configuration, shaping of pressure-travel relationships may be accomplished by varying the initial area exposed to burning by varying grain size. Similar effects illustrated in Figure 1-5 result as grain size is increased (Figure 1-6).

Similarly, comparative results of independently varying composition (quickness) or web thickness (a combination of size and configuration parameters) can be demonstrated. In adapting such relationships to specific gun systems, a compromise of their characteristics must be utilized. Hand and shoulder weapons require pressure-travel relationships that minimize muzzle blast at the expense of reaching high peak pressures and, characteristically, utilize "quick," degressive, small-grained propellant design. High peak pressures, avoided because of design problems

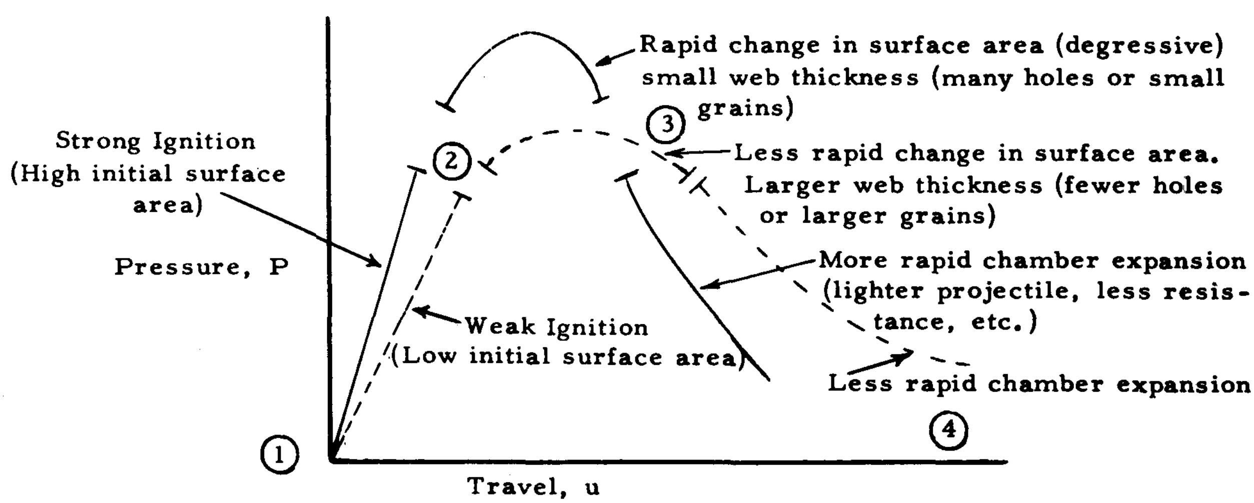


Fig. 1-4 Pressure-travel relationship.

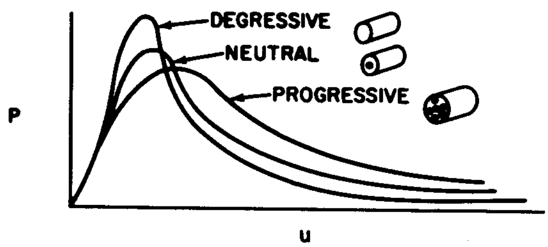


Fig. 1-5 Effects of grain configuration on pressure-travel curves. (Charge weight is equal in each case.)

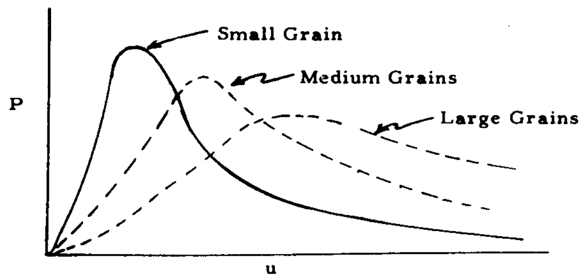


Fig. 1-6 Effects of independently varying grain size. (Charge weight is equal in each case.)

of gun tubes for cannon, are minimized by propellant designs based on "slow," progressive burning configurations of large size.

1-7.3 DENSITY OF LOADING

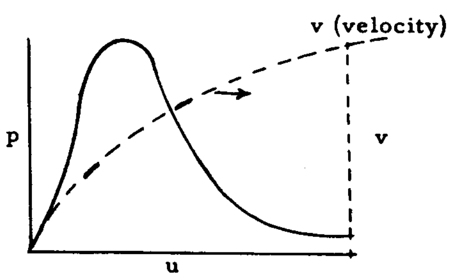
The various types of guns, with different calibres and lengths, and each with its own muzzle velocity design, present special requirements for the propellant. The lengths of travel of the projectile in the bore and, consequently, the times of its travel, differ greatly. In addition, the volume of the powder chamber and the weight of the projectile introduce elements which must enter into the selection of a propellant for a gun.

Since muzzle energy is directly dependent on the amount of charge burned, it becomes necessary to consider feasible means for increasing the total amount of energy (potential) released in the form of useful work done on the projectile. It is possible, by choosing increasingly large charges of slow powders, to obtain increased velocity without exceeding the maximum allowable pressure. Efficiency will be correspondingly lowered; hence it is not advantageous to fire slow powder in a gun not designed for it. The irregularity in the initial muzzle velocity is closely associated with overall efficiency which, if lowered enough, permits unburned powder to increase irregularity, muzzle blast, and flash. With slower propellants, the point of maximum pressure occurs later, thus demanding stronger and heavier construction over the length of the tube. Conversely, increasing the weight of charge of powder of given quickness increases the maximum pressure attained and causes it to occur sooner in the travel of the projectile.

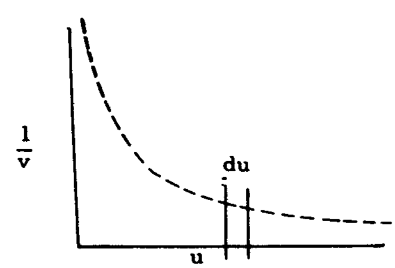
Despite the inherent disadvantages, the demand for high muzzle velocity dictates further development of guns with flat pressure-travel curves, as evidenced by developments using mechanism of a propellant charge traveling the tube length with the projectile.

1-8 PRESSURE-TIME RELATIONSHIPS FOR GUN SYSTEMS

The frequency with which propellant burning characteristics are plotted, using time as a parameter, and the trend toward use of pressure-time relationships obtained from experimental investigations, warrants a brief review of the comparison of this manner of data presentation with those discussed previously.



or



For any given pressure-travel plot (analogous to pressure-volume diagrams) the relationship of projectile velocity versus travel in the gun provides the basis for relating distance and time for pressure readings. Thus, a given pressure-travel diagram dictates the accelerations imparted to a projectile, and hence velocity v. The time relationship then results from the integral of an inverse velocity-travel function, i.e.,

$$t = \int_0^u \frac{1}{v}\, du$$

which permits evaluation of a travel-time relationship. A characteristic pressure time relationship may be then determined. (A characteristic plot is shown in Figure 1-7.) Timewise, the peak pressure occurs later in the cycle, since the projectile moves at relatively low velocity during the early phases of its travel down the gun tube.

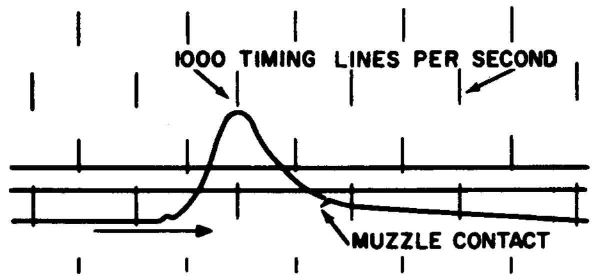


Fig. 1-7 Pressure-time relationship determined experimentally.

1-9 EFFICIENCIES OF GUN AND CHARGE

Two efficiencies are in general use as expressions of the overall behavior of a given gun charge-projectile combination. Piezometric efficiency is associated with the flatness of the pressure-travel curve, $\frac{\text{mean pressure}}{\text{peak pressure}}$ where the mean pressure is that which, if exerted against the projectile over the total length of travel, would produce the observed muzzle velocity. Useful in barrel design, a high piezometric efficiency means a shorter and lighter barrel, provided that chamber volume has been increased. It implies high muzzle pressure relative to peak pressure, but indicates final burning of the propellant near the muzzle for greater blast and risk of inferior regularity. Successive charges in a howitzer provide for higher piezometric efficiences as size of the charge is increased. Efficiencies of the order of 50% are common. Values of 40% are normal for low charge firings from howitzers and infantry mortars where regularity is of maximum importance. Values up to 60% suit A.T. gun design. The highest known values under experimental conditions have reached 75 to 90%.

Ballistic efficiency, defined as the ratio of muzzle energy to the potential energy of the propellant (expressed as a percentage), is a measure of the utilization of the energy in the charge. A high ballistic efficiency is obtained by burning the charge as early as possible in the projectile travel; just the opposite of requirements for a high piezometric efficienc,

1-10 DEVELOPMENT OF TECHNIQUES

Until 1930, the central problem of theoretical interior ballistics was confined to a single problem: Given the characteristics of projectile and gun and a knowledge of the behavior of the charge in a closed vessel, predict muzzle velocity and peak pressure. The experimental work was based on the copper "crusher gauge" (see Appendix A) that was little changed since its invention by Novel in 1860, and the Boulenge chronograph which appeared about the same time. By 1935, perfection of piezoelectric pressure gages and the knowledge that accurate pressure-time curves would soon be obtained in guns, spurred the theoretical outlook. Closed vessel theories were replaced by treatments involving physics and physical chemistry, and the whole

course of the phenomenon had to be developed, not only the salient features. Empiricisms relating velocity and peak pressures can be traced back to Poisson (1826), and are associated with the names of Vallier, Heydenreich, and LeDuc (the latter's methods in use as late as the mid 1940's) as being applicable over a limited range of conditions as a way of interpolating performances of nearly identical guns and charges. Re'sal's relations for shot and propellent gases, Sarrau's equation of combustion, and the Gossot-Liouville solution, obtained wider generality from a given quantity of data. Roggle was able to demonstrate relations between pressure-time curves for different shapes of propellant. Continuous refinements and applications of new theories by Dr. J. C. Hirschenfelder and his contemporaries; vastly improved instrumentation techniques which now include accurate time-distance indicators based on doppler effects; tourmaline pressure gages; radioactive powder grains; and the solution of the complex equations of thermochemistry and dynamics by modern analog and digital computing machines, have greatly extended current treatment of the subject.

1-11 SIMPLIFIED VELOCITY COMPUTATIONS

Many formulas and equations have been developed for the expressions of projectile velocities and powder pressures as functions of time or distance traveled by the projectile in the bore. The formulas to be used in this study are those developed by Colonel (then Captain) Camille LeDuc, about 1895. The LeDuc formulas are empirical, but they are sufficiently trustworthy to give approximations of velocities and pressures to be expected. They have academic value in terms of simplicity and are studied at this time to permit evaluation of pressure, travel, velocity, and time relationship in a manner within the scope of this course. They will be used later to solve problems of recoil. The complexities of exact technique of solving the interior ballistic problem preclude further consideration in this text.

The LeDuc equations for velocity as a function of travel are based on the translation of a hyperbolic curve (Figure 1-8), whose general equation takes the form:

$$v = \frac{au}{b + u} \tag{1-1}$$

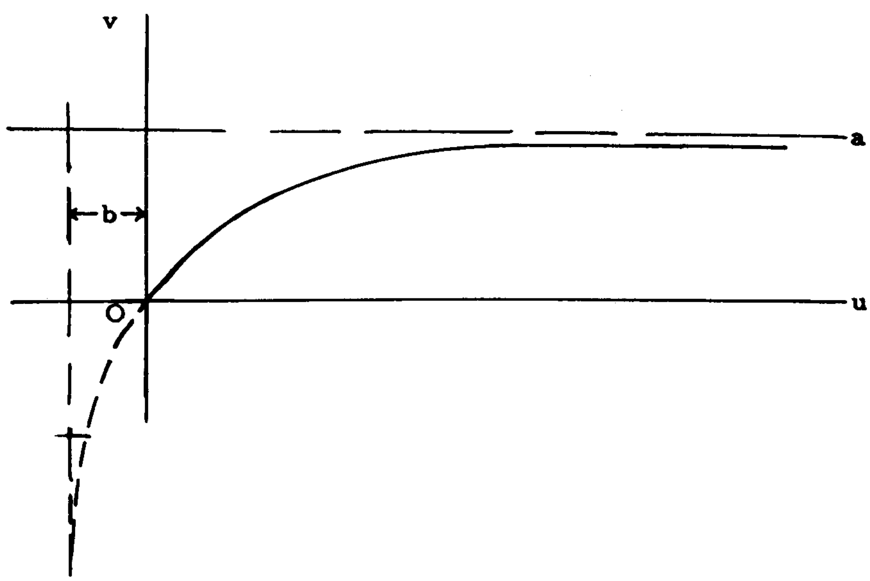


Fig. 1-8 LeDuc velocity-travel relationship.

where

v is velocity of the projectile at any point in the bore, ft/sec
u is travel of the projectile in the bore, ft
a is empirical constant, ft/sec
b is empirical constant, ft

For muzzle conditions (1-1) may be written

$$V = \frac{aU}{b + U} \tag{1-2}$$

where

V = muzzle velocity, ft/sec
U = length of bore, ft

The values of the constants a and b must be determined empirically and checked and corrected by actual test firings in order that the best approximation to the actual velocity can be determined. The positive branch of the curve approaches a as a limit. Thus, if the gun tube were of infinite length and the powder gases allowed to expand without limit, the expression $\frac{u}{b+u}$ would approach unity, and v would equal a. This may be seen graphically in Figure 1-8.

There is a definite relationship between the value of b and the travel of the projectile to the point of maximum pressure. It can be shown by calculus that when the pressure, and hence acceleration, is a maximum, the relationship $u = \frac{b}{2}$ exists (see Par. 1-13).

In practice, with the LeDuc Method a and b are determined by choosing them so as to reproduce muzzle velocity (1-2) and maximum pressure in a number of typical cases, and thus determine empirical relationships.

For each powder manufactured, a powder constant which represents the relative quickness of the powder is determined. This value is dependent upon such factors as the web thickness, the size of grain, and percentage of remaining volatiles, and is largest for slow powders. It may be seen that b will be directly proportional to this constant, since, for example, a slow powder (large constant) will cause the point of maximum pressure to occur farther down the bore than will a fast powder, and the magnitude of b varies with the distance to this point of maximum pressure.

From (1-1), $v = \frac{au}{b+u}$, the velocity for any point in the bore may be obtained.

The kinetic energy of the projectile at any time is $\frac{1}{2}\frac{wv^2}{g}$, where w is the weight of the projectile in pounds.

The empirical constants, a and b, are computed from the results of experimental firings adjusted to the propellant used. For example:

$$a = 6823 \frac{\omega}{w}^{1/2} (\Delta)^{1/12}$$

where

Δ = density of loading
ω = weight of charge, lb
w = weight of projectile, lb

(The constant 6823 represents the potential of nitrocellulose propellant.)

$$b = \beta \left(1 - \frac{\Delta}{\delta}\right) \left(\frac{S}{w}\right)^{2/3}$$

where

β = powder constant, or a measure of the "quickness" of the powder (varies inversely as the velocity of burning)
δ = specific gravity of the powder (usually between 1.5 and 1.6)
S = volume of the powder chamber, cu in.

1-12 EFFECTS OF VARIATIONS IN THE GUN PROJECTILE SYSTEM

The effects of variations of the propellant on the velocity and pressure have been discussed. For a charge of given composition, grain geometry, and grain size, the variations in performance are indicated in the following paragraphs.

1-12.1 GUN TUBE LENGTH

By examining LeDuc's equation it may be seen that if an increase is made in the length of the gun tube, the muzzle velocity should rise. There is an actual increase because the powder gases are all being expanded within the tube, rather than released to the air behind the projectile. Up to a certain point the gun tube may be lengthened to increase the muzzle velocity; however, there is a practical limit beyond which the additional velocity does not justify the added weight.

1-12.2 GUN CHAMBER

If the volume of the powder chamber is varied for a given charge, the density of loading will vary. Such variations may occur when a different projectile is used; the projectile is not uniformly seated; or when the charge is used in a different gun. In general, an increase in the density of loading will cause an increase in velocity and maximum pressure, but will decrease the length of travel to the maximum pressure point. For example, a 1% increase in density of loading in a 120-mm gun increases the velocity 0.3%, or from 3100 ft/sec to 3110 ft/sec.

1-12.3 PROJECTILE WEIGHT

A decrease in projectile weight has an effect on the pressure-travel curve similar to that of an increase in grain size. The peak maximum pressure is lowered, its position is moved forward, and the area under the curve is decreased. The muzzle energy is lessened but the lowered shell weight has the effect of increasing muzzle velocity. The muzzle velocity varies approximately inversely as the square root of the weight of the projectile; or more accurately, $y = Kw^{-n}$, n varying between 0.35 and 0.50. The lower value represents the effect of a large decrease in projectile weight. This same effect can be shown by examining LeDuc's equation for velocity and equations for a and b. (Consideration of the expression for the energy imparted to the projectile within the gun, $1/2\ MV^2$, will show that V varies inversely as $(w)^{1/2}$ if the total energy imparted is the same.)

1-12.4 DENSITY OF LOADING

A change in density of loading may result from changes in the weight of charge or changes in the volume of the powder chamber; and the changes in the volume of the powder chamber may be caused by using a different type of gun or projectile, or by nonuniform seating of the projectile. In general, a decrease in the density of loading decreases the velocity and the maximum pressure but increases the length of travel to the point of maximum pressure.

With the same gun and projectile, a change in density of loading is obtained only by changing the weight of powder charge or by nonuniform seating of the projectile. In either of these instances, for small changes, the approximate rule is: The velocity varies as the square root of the density of loading.

1-12.5 SECTIONAL DENSITY

If the weight of a projectile of a given diameter is reduced, the projectile is said to have a decreased sectional density, defined as:

$$\frac{\text{weight}}{(\text{diameter})^2}$$

where the weight is in pounds and the diameter is in inches. Representative values for various projectile types and calibers are:

Projectile Type and Caliber	Sectional Density
155-mm HE	2.557
90-mm AP	1.892
90-mm HVAP	1.76
76-mm HEP	1.104
.30 BALL M2	.237
.30 AP M2	.260

Low sectional density is desirable from an interior ballistics viewpoint but undesirable from an exterior ballistics viewpoint, since the projectile has less inertia and will be more easily retarded by the air. As a means of providing low sectional density of the projectile while it is in the gun, and increasing this factor while the projectile is in flight, methods employed have as a goal the decrease in diameter of the projectile after it leaves the gun tube. Projectile types utilizing this principle are:

(a) Discarding sabot projectile.
(b) Folding skirt projectile (used in a tapered bore weapon).

Other methods of reducing the sectional density are the composite rigid projectile (HVAP) and the Russian Arrowhead. In these cases, the sectional density remains low during the flight of the projectile.

1-13 PRESSURE COMPUTATIONS

An expression for pressure in the gun tube may be derived from LeDuc's velocity equation. The rate of change of momentum:

$$F = Ma$$

$$PA = \left(\frac{w}{g}\right)\left(\frac{dv}{dt}\right)$$

$$P = \left(\frac{w}{Ag}\right)\left(\frac{dv}{dt}\right)$$

P = pressure producing acceleration, psi
A = cross-sectional area of the gun tube, sq in.

Differentiating LeDuc's equation for velocity,

$$\frac{d}{dt}\left(\frac{au}{b+u}\right) = \frac{(b+u)\,a\left(\frac{du}{dt}\right) - au\left(\frac{du}{dt}\right)}{(b+u)^2}$$

$$= \frac{ab}{(b+u)^2}\left(\frac{du}{dt}\right)$$

But,

$$\frac{du}{dt} = v = \frac{au}{b+u}$$

Substituting in the expression above,

$$\frac{dv}{dt} = \left(\frac{ab}{(b+u)^2}\right)\left(\frac{au}{(b+u)}\right) = \frac{a^2bu}{(b+u)^3}$$

Thus

$$P = \frac{wa^2bu}{Ag(b+u)^3} \qquad (1\text{-}3)$$

Since maximum pressure must correspond to the point of maximum acceleration,

$$\frac{d}{dt}\left(\frac{dv}{dt}\right) = 0$$

or

$$\frac{d}{dt}\left(\frac{a^2\,bu}{(b+u)^3}\right) =$$

$$\frac{(b+u)^3\,(a^2b)\left(\frac{du}{dt}\right) - (a^2bu)\,(3)\,(b+u)^2\left(\frac{du}{dt}\right)}{(b+u)^6} = 0$$

or

$$b + u - 3u = 0, \text{ whence } \frac{b}{2} = u$$

Substituting in (1-3) above,

$$P_{max} = \frac{4\,wa^2}{27\,Agb} \qquad (1\text{-}4)$$

As noted previously, actual tube pressure must overcome friction; force the rotating band through the rifling; impart rotation to the projectile; and produce acceleration. The actual bore pressure, which has been found experimentally to be approximately 1.04 times the pressure producing translation of the projectile [see (1-3)], is given by the formula

$$P(\text{actual}) = \frac{1.04wa^2bu}{gA(b+u)^3} \qquad (1\text{-}5)$$

Also from (1-4), the actual maximum pressure is given by the formula

$$P_{max}(\text{actual}) = \frac{4.\,16wa^2}{27\,Agb} \qquad (1\text{-}6)$$

1-14 EFFECTS OF VARYING CONDITIONS IN SERVICE

During the service life of a gun tube, a number of variables may affect its ballistic performance in a manner which a designer may not predict, but which must be anticipated. Wear characteristics of the bore vary widely between the extremes of large, low velocity howitzers, and hypervelocity tank and anti-tank guns. Environmental conditions such as ambient temperature, gun temperature, deterioration of ammunition in storage, and others, thus may affect the initial conditions for the exterior trajectory of the projectile. Examples of two methods by which such conditions are resolved to standard conditions are indicated here. Firing tables include means for absorbing the effects of nonstandard conditions into firing data, and tube serviceability standards are used to predict service life and effects of wear on specific guns firing specific types of ammunition.

1-14.1 TEMPERATURE OF THE POWDER

Firing tables are based on a powder temperature of 70°F, at the time of firing. An increase in this temperature increases the potential and the burning rate of the propellant, giving a greater muzzle velocity. Conversely, a decrease in the powder temperature reduces the velocity. A tabulation of the effects of variation from standard powder temperature is incorporated in the tables to enable the necessary corrections to be made in the firing data. An extract from firing tables for the 105-mm howitzer is shown in Table 1-1.

1-14.2 TEMPERATURE OF THE GUN

A change in muzzle velocity will occur because of high gun temperature due to rapid fire. As an example, 30 rounds fired rapidly in a 90-mm gun will cause a breech metal temperature of about 275°F. If a round is left in the gun before firing, the powder will be affected by this temperature; however, if the round is fired quickly, there will be no appreciable change in powder temperature and consequently, no velocity change. The spontaneous firing of an overheated round left in a hot breech recess is commonly termed "cook-off."

1-14.3 EROSION IN THE GUN BORE

Erosion is the process of removal of metal from the surface of a gun tube by the movement at high velocities of high-temperature gases and residues generated from the burning of the propellant, as well as by the movement of the projectile through the bore. Erosion is often divided into three phases:

(a) Gas erosion. The first indications of this type of erosion are hairline cracks or a checkering effect near the origin of rifling. This is probably caused by continued expansion and contraction of the metal of the gun tube in conjunction with the brittleness of the metal caused by the absorption by the gun tube of carbon and nitrogen from the powder, producing a brittle carbide or nitride. This checkering or cracking is not erosion in itself but makes it easier for the hot gases moving at high velocity to wash away the metal. Figure 1-9 shows the checkering and gas erosion near the origin of rifling and the gradual wearing away of the rifling.

(b) Scoring. Scoring is attributed to a nozzle or vent action of the gas escaping past the rotating band. Sometimes tool marks or rifling defects start the scoring because of lesser obturation or sealing by the rotating band at the defect. Once started, scoring, unlike gas erosion, increases rapidly with each round although it does not usually become evident until after several rounds have been fired. Scoring usually begins on the upper part of the bore around the 12 o'clock region, due to the weight of the projectile causing the greater clearance at the top when seated. This is usually more evident in guns firing separate-loaded ammunition. When firing is done

TABLE 1-1 EXTRACT FROM FIRING TABLES FOR 105-MM HOWITZER. SHELL H.E. M1 MV = 710 FT/SEC, CHARGE 2

Change in Velocity Due To Change in Temperature of Powder			
Temperature of Powder, °F	Change in Velocity, ft/sec	Temperature of Powder, °F	Change in Velocity, ft/sec
0	−22	50	−6
10	−19	60	−3
20	−16	70	0
30	−13	80	+3
40	−9	90	+6
50	−6	100	+9

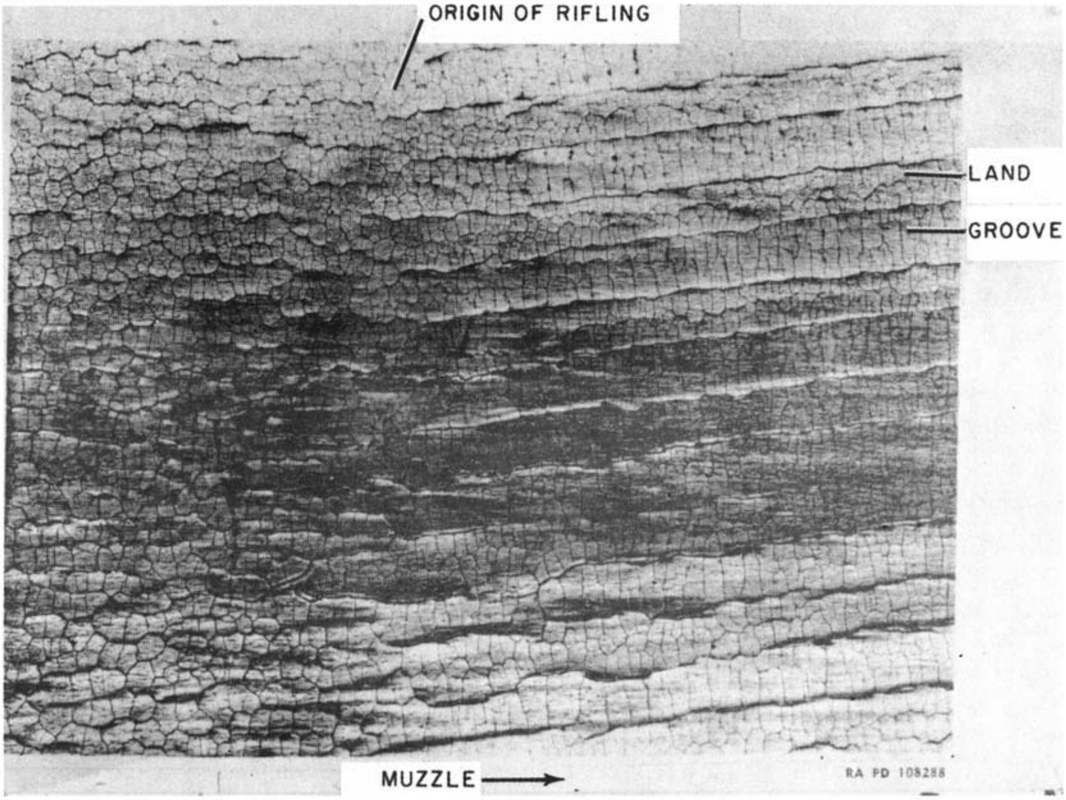


Fig. 1-9 Advanced gas erosion at origin of rifling near 12 o'clock of 155-mm gun, M2. Note complete obliteration of lands. (Extract TB 9-1860-2)

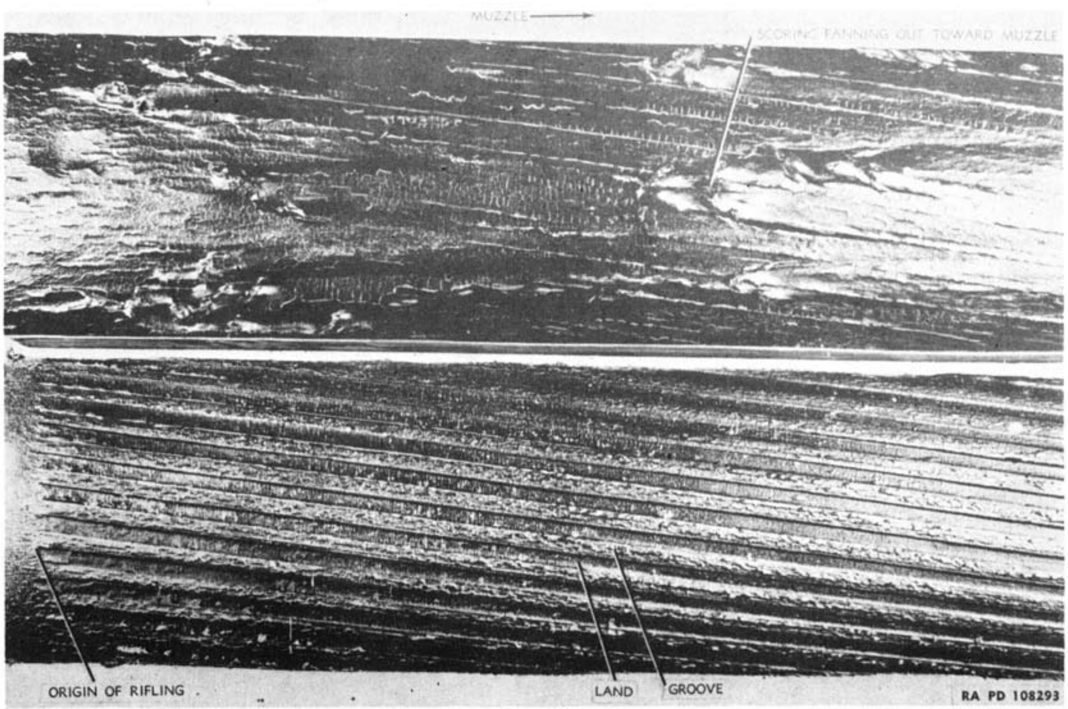


***Fig. 1-10** Impressions showing scoring at 12 o'clock (top) and gas erosion at 6 o'clock (bottom). Bottom also shows light scoring in the grooves. Taken from 155-mm gun, M2. (Extract TB 9-1860-2)*

with a hot gun or at faster rates, after scoring has once started, scoring can become very severe. Deep scoring reduces the strength of the gun tube, but most guns become too inaccurate for further use before scoring becomes dangerous. Figure 1-10 shows a typical scoring at the 12 o'clock position in a 155-mm gun.

(c) Abrasion. Abrasion is a slow mechanical wearing away of the lands after a large number of rounds have been fired. The greater wear usually occurs at the 6 o'clock position at the origin of rifling because of the greater friction between the projectile and the bore at the bottom. This wear permits the rotating band to drop, allowing a larger clearance between the top of the rotating band and the tube, accelerating gas erosion and then scoring.

The primary effect of erosion is a drop in peak pressure and a resulting loss of muzzle velocity, which results in a corresponding decrease in maximum range. Under actual firing conditions with a worn gun, there is a small range loss not accounted for by the loss of velocity. This may be due to increased yaw or other reasons. Since this loss is small, nearly all the range loss evidenced can be attributed to muzzle velocity loss. Allied to the range loss is the increase in time of flight for the same ranges in antiaircraft weapons. This is important when considered as additional time for movement of the target. The loss in accuracy in most guns due to erosion is insignificant except in advanced stages when rotating bands may be sheared off.

In order to fully appreciate the actual values involved in gun erosion, consider as an example the erosion effects on a particular gun, the 90-mm gun, M3, in the M46 medium tank. The erosion in this gun is characterized by a smooth, even wear of the lands with scoring during latter stages. As erosion occurs, the bore is enlarged. The drop in velocity (based on the diameter between the lands, in inches, measured at a point 24.85 inches forward of the breech end of the tube) which may be expected at any degree of wear, is shown in Figure 1-11 for the high explosive projectile M71, and for the armor-piercing capped projectile M82.

For a given weight of armor-piercing projectile,

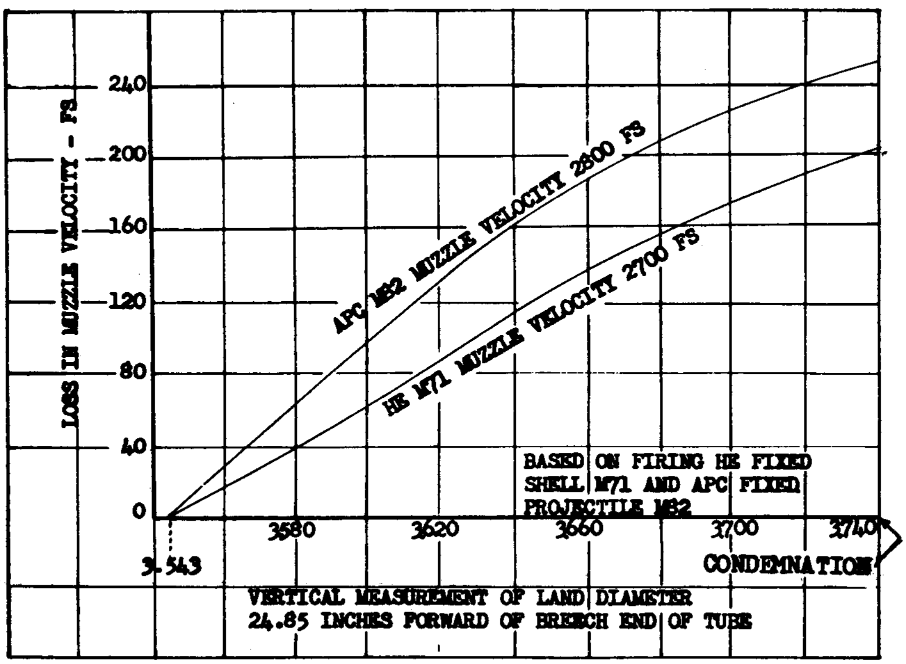


Fig. 1-11 Muzzle velocity loss as a function of bore measurement for tubes used in 90-mm guns M1, M2, and M3. (Extract TB 9-1860-2)

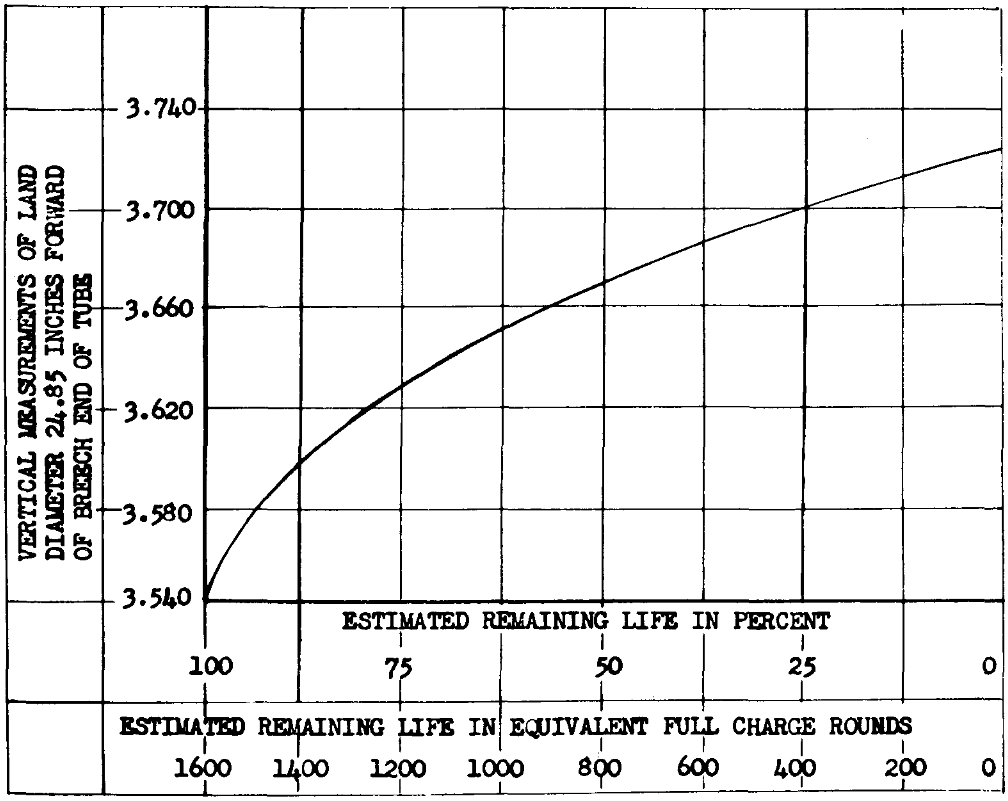


Fig. 1-12 Remaining life as a function of bore measurement for tubes used in 90-mm guns M1, M2, and M3. (Extract TB 9-1860-2)

a loss in muzzle velocity is reflected in striking velocity. Therefore, armor penetration is decreased, or the range at which a given thickness of armor can be penetrated is decreased. The condemnation point for tubes firing armor-piercing capped projectile M82, occurs when the velocity has dropped to 2557 ft/sec. At this stage windshields may become separated from the projectile or rotating bands may strip off while the projectile is still in the bore. The condemnation point for the M82 APC projectile is shown on the graph in Figure 1-11, represented by a 243 ft/sec loss in muzzle velocity. In practical terms this means that at a range of 2000 yards this projectile will penetrate only 3.6 inches of homogeneous armor instead of 4.15 inches which would be expected from a new gun.

The remaining life expectancy in number of rounds of this 90-mm gun is shown in Figure 1-12. That for the 105-mm howitzer M2A1 is based on equivalent service rounds computed for weapons capable of firing zone charges. (See Table 1-2.)

1-15 INITIAL CHARACTERISTICS OF GUN-LAUNCHED PROJECTILES

Interior ballistic problems normally center about the motion of the projectile while under the influence of the launcher, while exterior ballistics usually is associated with the flight characteristics from that point to the target. The simplicity of such definitions fails to indicate, however, the launcher influence on the initial conditions of the trajectory. In the case of gun-launched projectiles, a number of phenomena occur while the projectile is in the vicinity of the gun tube and must also be evaluated. Currently, most of these problems are the concern of interior ballisticians; however, the subject is of sufficient importance that it has often been called "transition ballistics." The launchings of guided or ballistic missiles, rockets, and for the most part projectiles from recoilless weapons, are concerned to a far less degree.

TABLE 1-2 EQUIVALENT SERVICE ROUNDS SHOWING EROSIVE EFFECT OF DIFFERENT CHARGES

Gun and Firing Tables	Charge	No. of Rounds Equivalent in Erosion Effect to One Full Charge (or Service Round)	Equivalent Erosion in Decimals
75-mm Gun, M 2	Supercharge	1	1.00
FT 75 AF 1	Normal charge	6	.16
	Reduced charge	53	.019
105-mm How., M 2	7	1	1.00
	6	3	.33
FT 105 H 3	5	10	.10
	4	20	.050
	3	40	.0250
	2	70	.0143
	1	120	.00833
105-mm How., M 3	5	1	1.00
	4	3	.34
FT 105 L 2	3	7	.15
	2	13	.079
	1	23	.043

1-15.1 INITIAL AIR EFFECTS

As the projectile moves forward in the barrel, it pushes the air mass in front of it, causing the latter to emerge first from the muzzle. The internal air mass, now traveling at a high velocity, strikes the outside air which is at rest, and creates a shock wave which develops spherically and disturbs the outside air. This condition is immediately followed by a rush of small amounts of powder gas which have forced their way ahead of the projectile and hence emerge from the muzzle before it. As the base of the projectile clears the muzzle, the main mass of the propellent gas begins to pour out into the already turbulent outside air. At this instant the velocity of the gas is equal to that of the projectile, but because of the tremendous gas pressure present, the former increases suddenly, causing the gas to rapidly overtake and pass the projectile. During this phase the gas develops a maximum velocity of more than twice that of the projectile and consequently imparts to the latter an additional thrust, thereby causing it to reach its maximum velocity not at the muzzle, but at some short distance in front of the muzzle.

Because of its small mass and the resistance to motion which it meets, the gas loses velocity very rapidly. In small arms, for example, the bullet overtakes the gas at approximately 35 cm from the muzzle. Shortly thereafter the projectile overtakes and pierces the report wave (the wave which produces the noise of the exploding propellant). At this instant the projectile is accompanied by the normal head wave which is defined as the projectile shock wave. It should be noted that a shock wave cannot form on the projectile unless the relative velocity of the projectile and the surrounding gaseous medium is equal to, or exceeds the speed of sound. During the time the projectile was passing through the powder gas envelope, this condition did not exist, and hence no head wave was formed. However, at the instant the projectile pierced the report wave, the required conditions existed and a head wave was formed.

Obviously in guns with a high cyclic rate of fire some exterior ballistic effect must be present due to gas stagnation, since the turbulence of the gaseous medium in the vicinity of the muzzle creates a condition of instability.

The stagnation or pressure limit created in front of the muzzle is the result of high velocity propellent gases emerging and compressing the initially still air, thus creating a marked retardation effect. An envelope of gas is formed with maximum pressure existing at the intersection of the stagnation line and a prolongation of the axis of the bore. The cycle of events, described by a related series of Schlieren photographs (Figure 1-13) continues as long as gas under high pressure continues to emerge from the muzzle. As the pressure subsides, the stagnation line moves towards the muzzle of the gun. The phenomenon of muzzle flash as a problem associated with propellants, and the chemical and mechanical means of combating the effects have been discussed. The effects of the air disturbances described here are directly associated with the cause and control of muzzle flash.

1-15.2 VERTICAL JUMP

When a gun has been made ready for firing, the axis of the bore forms, with the line of sight, an angle called the angle of elevation. From the viewpoint of normal expectancy, it would appear that the projectile on leaving the bore would follow initially the path determined by the line of elevation. Such is not the case, however, for when vertical jump occurs the projectile actually leaves the gun on a line of departure whose angle is greater than that of the line of elevation. (See Par. 3-2 and Figure 3-5, Part 2.)

When a projectile is launched from a gun, a number of things occur which cause the phenomenon of vertical jump. While the gun is at rest, the axis of the bore does not exist as a straight line but rather as a curve, concave down.

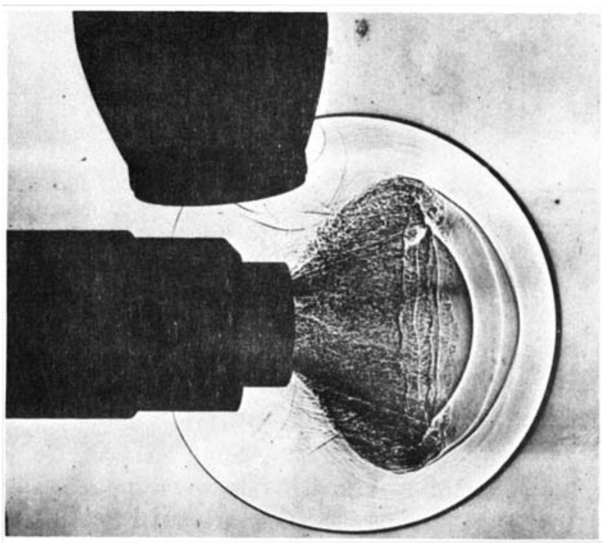


Fig. 1-13 (1) Effects of projectile emerging from muzzle. (Spark photograph of gun being fired.) Photograph No. 1 was taken before the bullet had emerged from the muzzle. The dark edged circle is actually a spherical shock wave. It is formed when the air column existing in the bore at the instant of firing, strikes the outside atmosphere at supersonic velocity. The gray, turbulent area within the circle is powder gas which has leaked ahead of the bullet. The dark object at the top of the photograph is a microphone which was used to trigger the spark, thus taking the picture.

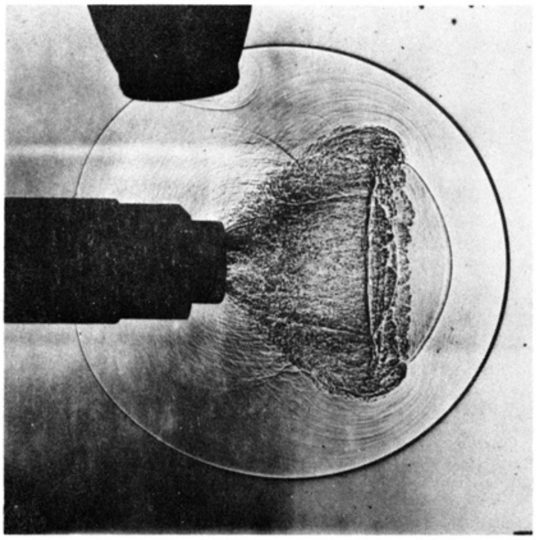


Fig. 1-13 (2) Effects of projectile emerging from muzzle. (Spark photograph of a gun being fired.) Photograph No. 2 depicts conditions perhaps a microsecond or less later than in (1). The bullet is still inside the barrel.

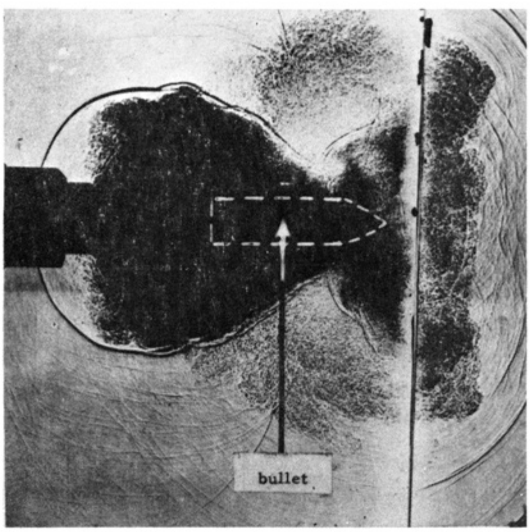


Fig. 1-13 (3) Effects of projectile emerging from muzzle. (Spark photograph of a gun being fired.) Photograph No. 3 shows the bullet emerging from the muzzle. It is partially obscured by the powder gas. The shock wave has continued to expand but is rapidly decelerating and will soon be pierced by the projectile which is retarded by the atmosphere to a much smaller degree.

The longer the gun tube, the more pronounced is this curve. A projectile passing through the bore at high velocity will cause the gun tube to be whipped rapidly upward, producing a condition similar to the straightening of a coiled hose when water under pressure is first allowed to pass rapidly through it. Due to the nature of the forces involved, as well as to the elasticity of the metal, the gun tube at the instant of projectile release is slightly concaved upward. The condition just described has been referred to as "gun tube droop." A second factor, whose vertical component contributes to vertical jump, results from the reaction of the gun tube to the rotation of the spinning projectile. With a projectile rotating clockwise as viewed from the breech of the gun, the gun tube will tend to be twisted in a counterclockwise direction. A third factor results from the sudden shifting of the center of gravity of the system as the projectile speeds down the bore. This effect tends to cause the muzzle of the gun to move towards the ground. A fourth factor is the lack of complete carriage stability, and this may be combined with a lack of complete rigidity with regard to various parts of the gun and carriage. The problem of carriage stability will receive later treatment in this text. The factors affecting vertical jump exist, but to varying degree and direction; hence, vertical jump is determined experimentally. On a mobile carriage, such as the 105-mm howitzer, the vertical jump is 1.8 mils; for fixed carriages it is approximately 0.4 mils.

1-15.3 LATERAL JUMP

Lateral jump is defined as the difference in azimuth between the line of bore sight and the line of departure, and when it exists has a magnitude considerably smaller than that of vertical jump. It may result from some of the factors causing vertical jump, but more frequently occurs as a result of an unbalanced carriage condition or a bend in the bore. Where an unbalanced carriage condition exists, lateral jump increases slightly with increase in gun traverse. In stable carriages with split trails, lateral jump is usually negligible. A bend in the bore is a condition comparable to droop and results from unsatisfactory machining operations. Suitable means exist for detecting this defect,

which, if serious enough, becomes a cause for gun tube rejection. Normally, bend in the bore is held within specified limits, thus producing a negligible amount of lateral jump.

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CHAPTER 2

INTERIOR BALLISTICS–THRUST PROPULSION SYSTEMS

2-1 INTRODUCTION

Since World War II, the design of modern weapons has placed increasing demands on conventional systems in terms of range, velocity, accuracy, and flexibility. These demands have exceeded the capabilities of projectile-type systems as well as the capabilities of reciprocating engine-type aircraft to deliver an effective destructive missile against an enemy. In past centuries, lack of dependability and accuracy caused rejection of simple rockets as being ineffective, inefficient, and unpredictable despite their obvious potential. New propulsion techniques and modern scientific and technological advances have now, however, permitted the development of rocket motors and air breathing jet engines to the extent that modern weapons systems are increasingly centered about free rockets, guided missiles, and jet-powered supersonic aircraft which rely on the thrust-producing reaction motor as the propulsion means.

Within the broad category of reaction motors lies the solid or liquid fuel rocket motor and the jet. The solid and liquid fuel rocket motor carries its own oxidizer, permitting thrust to be developed within as well as outside the atmosphere. The liquid fuel jet engine relies on atmospheric oxygen to support combustion and is represented by turbo jet, pulse jet, and ram jet designs.

In this chapter the basic principles applicable to thrust propulsion by reaction motors will be discussed. Following this, the problems unique to rockets and jets are discussed separately as applicable to specific weapon propulsion requirements.

2-2 REACTION MOTOR PRINCIPLES

Contrary to popular beliefs, a reaction motor does not push against the air to obtain its thrust. The thrust is obtained by increasing the momentum of the working fluid and by a pressure differential.

Newton's third law of motion, paraphrased, states that "For any action, there is an equal and opposite reaction." The reaction motor is propelled on the basis of this principle. Thus, jet engines may be called reaction motors. This is not sufficiently specific, however, because any body moving in a fluid works on the reaction principle if it is self-propelled. For instance, the action of a conventional propeller consists of increasing the momentum of the air, and the propeller thrust is the resultant reaction. The ordinary propeller-driven missile or aircraft is not a form of jet propulsion because the working fluid is not ejected from within the vehicle. If the propeller were put in a duct and the air allowed to pass through the vehicle, one would then have mechanical jet propulsion.

A reaction motor consists essentially of a propellant supply system, a combustion chamber, and an exhaust nozzle (Figure 2-1). The purpose of the propellant system and the combustion chamber is to produce large volumes of high temperature, high pressure gases or heat energy. The exhaust nozzle then converts the heat energy into kinetic energy as efficiently as possible.

In a *solid propellant rocket* the combustion chamber may contain the fuel to be burned. In a liquid propellant rocket, or in a jet engine, the combustion chamber contains the combustion reaction only. The fuel is pumped and metered in from tanks outside of the chamber.

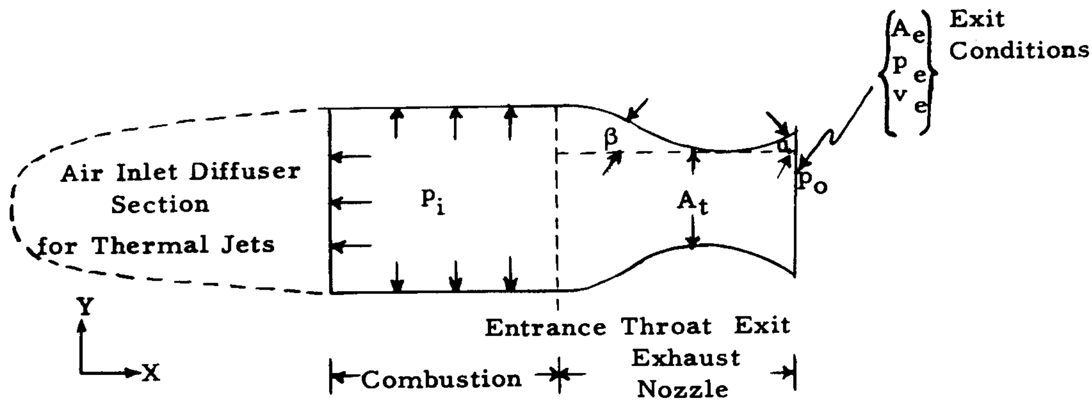


Fig. 2-1 Reaction motor with convergent-divergent nozzle.

2-3 THRUST

Thrust is the reaction experienced by the motor structure due to the ejection of high-velocity matter. Momentum is the product of the mass of a body and its velocity, and is a vector quantity. Newton's second law of motion states that the time rate of change of momentum of a body is a measure in direction and magnitude of the force acting upon it. In a rocket chamber, billions of molecules of the products of combustion are accelerated within a very short distance (the length of the rocket motor), from essentially zero velocity to exhaust velocities on the order of 6000 miles per hour. An applied force of great magnitude is required to impart such momentum to the exhaust gases. Newton's third law of motion states that there must be an equal and opposite reaction to this momentum-creating force. This equal and opposite reaction is the thrust of the rocket motor.

The term thrust, which has been used frequently up to now, should be defined before proceeding further. Thrust is an applied force used to produce motion in or alter the motion of a body. It is measurable in pounds of force. It should be noted that thrust is not a measure of work or horsepower: a reaction motor which is motionless develops no horsepower. At a velocity of 375 miles per hour, one pound of thrust will develop one horsepower. The relationship is as follows:

$$THP = \frac{\text{thrust (lb) velocity (fps)}}{550}$$

$$= \frac{\text{thrust (lb) velocity (mph)}}{375}$$

A rocket of the V-2 type that develops approximately 50,000 pounds of thrust at a velocity of 3750 miles per hour is developing 10 × 50,000 = 500,000 horsepower.

2-3.1 THE EQUATION FOR MOMENTUM THRUST

$$F = \frac{d}{dt}(mV) = m\frac{dV}{dt} + V\frac{dm}{dt} = 0 + \dot{m}V,$$

since V_e = constant

Thus

$$F = \dot{m}_e V_e - \dot{m}_a V_a \equiv \frac{\dot{w}_e}{g}(V_e) - \frac{\dot{w}_a}{g}(V_a) \quad (2\text{-}1)$$

where

F = thrust in pounds of force

$\dot{w}_e$ = weight rate of flow of exhaust products, lb/sec

V_e = velocity of exhaust products, ft/sec

g = 32.2 ft/sec^2

$\dot{w}_a$ = weight rate of flow of air entering, lb/sec

V_a = velocity of air entering relative to engine, ft/sec

In air breathing motors, e.g., turbojets, the mass of fuel is small compared to the mass of air, so $\dot{m}_e$ and $\dot{m}_a$ are near enough to being equal so that the equation becomes:

$$F = \dot{m}\,(V_e - V_a) \tag{2-2}$$

For rockets $\dot{m}_a$ and V_a are both zero, and the equation becomes:

$$F = \dot{m}V_e \tag{2-3}$$

2-3.2 THE GENERAL EQUATION FOR TOTAL THRUST

In the equation $F = \dot{m}V_e$, it was assumed that the exhaust pressure of the gases, p_e, was equal to the pressure of the surrounding medium, p_o. In the usual case, where $p_e \neq p_o$, there is an additional term, a function of the difference in pressure, which must be added to make the thrust equation strictly correct. In deriving a correct thrust equation, it can be stated as a starting point that the thrust of a rocket motor is the resultant of the pressure forces acting over the inner and outer surfaces. Thus,

$$F = \int_S PdS = \int_S P_i dS_i + \int_S P_0 dS_0 \tag{2-4}$$

where

S = total surface area
S_i = internal surface area
S_0 = external surface area
P_i = internal pressure
P_0 = external pressure

$$\int_S P_i dS_i = \text{net internal force} = mV_{e(x)} + P_e A_e \tag{2-5}$$

and

$$\int_S P_0 dS_0 = \text{net external force} = -P_0 A_e \tag{2-6}$$

Therefore,

$$F = \dot{m}V_{e(x)} + (P_e - P_0)\,A_e \tag{2-7}$$

or, using the nozzle angle correction factor λ, where $\lambda V_e = V_{e(x)}$ (see Par. 2-6.4),

$$F = \lambda \dot{m} V_e + (P_e - P_0)\,A_e \tag{2-8}$$

2-4 SPECIFIC IMPULSE

Impulse is introduced as a measure of the performance of the rocket motor because the amount of propellant necessary is almost the same for the same total impulse, no matter whether this impulse is delivered as a large thrust for a short duration or a small thrust for a long duration ($I = \int F\,dt$).

Of particular interest to rocket design is the amount of thrust delivered per weight rate of flow of propellant, $F/\dot{w}$. This quantity is a function of the design of the motor which is based upon the expected thermodynamic properties of the gas, defined in Part 1 (Sources of Energy) as specific impulse:

$$I_{sp} = \frac{F}{\dot{w}} = \frac{(P_e - P_0)A_e}{\dot{w}} + \frac{\lambda\,V_e}{g} \tag{2-9}$$

If I_{sp} is multiplied by the gravitational constant g, the resultant value is defined as the effective gas velocity V_j, with the units ft/sec. Thus,

$$V_j = gI_{sp} = \frac{gF}{\dot{w}} = \frac{g(P_e - P_0)A_t}{\dot{w}} + \lambda V_e \tag{2-10}$$

or assuming the nozzle correction factor as one ($\lambda = 1$):

$$V_j = \frac{F}{\dot{m}} = \frac{(P_e - P_0)A_t}{\dot{m}} + V_e \tag{2-11}$$

2-5 ROCKET MOTOR THERMODYNAMICS

The configuration of the nozzle is important to good nozzle design, but thermodynamic considerations play as large a part. Consider Figure 2-2, where, if the valve is cracked, a small flow of gases will enter the chamber and cause pressure in the chamber to rise until the weight rate of escape of gases through the exit section equals the rate of flow of gases through the valve. After this has occurred the flow will remain steady (a "steady-state flow" condition will exist). After this steady flow condition, the chamber pressure (P_i) becomes a fixed or "equilibrium" pressure value. If the valve is opened further, more flow will result, and after a steady state again is

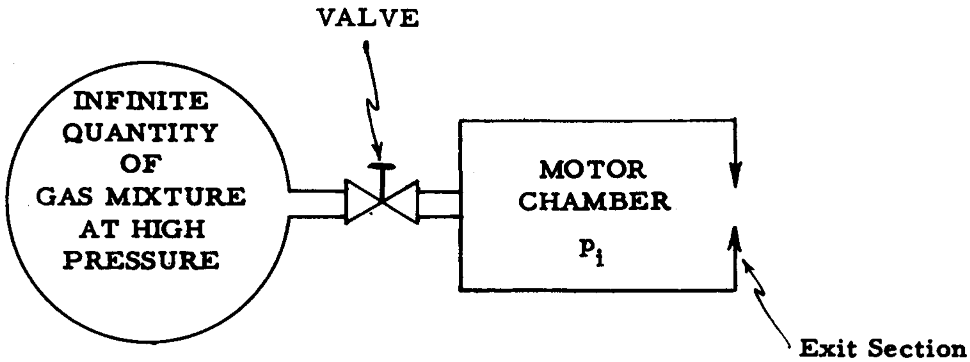


Fig. 2-2 Schematic flow diagram.

reached, a new flow rate and a new (higher) equilibrium chamber pressure (P_i) will exist.

Thus, it might be concluded that as the flow rate is increased (by stepwise valve openings) the chamber pressure increases. For a reaction motor mounting a well-designed exit section, this is always true. If a further assumption is made that the temperature of the gases in the chamber (T_i) and the outside pressure (P_o) remain constant, then the equilibrium temperature, equilibrium pressure, and equilibrium velocity of the gases at any one condition of steady-state flow will vary with one another. However, as the gases flow down the chamber and into the throat of the nozzle, the gas temperature will fall as the thermal energy of the gases is converted to kinetic energy. However, a continued increase in flow rate, and a subsequent increase in equilibrium chamber pressure, will not produce an infinitely increasing velocity or decreasing temperature. Rather, above a critical equilibrium chamber pressure ($P_{crit} = P_i$) although chamber pressure is again increased, further velocity and temperature changes will not occur. This does not mean however, that more mass cannot be made to flow through the motor. Density of the gases may and does increase as the valve opening is increased further. The mass rate of discharge is described as:

$$\dot{m} = \rho_t A_t V_t \tag{2-12}$$

where

ρ_t = density of gases at throat, slugs/ft³
A_t = area of throat, ft²
V_t = velocity of gases at throat, ft/sec

When $P_i > P_{crit}$ and since in any given case A_t is constant, then $\dot{m}$ = (constant) (ρ_t); or the mass rate of discharge is proportional to gas mixture density. Thus, above the critical pressure the mass rate of flow is a function of the thermodynamic nature of the gases discharged. The behavior of a nozzle operating above P_{crit} is called "nozzling."

Evaluation of motor design involves specific thermodynamic relationships. From the ideal gas law,

$$PV = nRT;\ P = \frac{nRT}{V} = n\rho RT, \tag{2-13}$$

and the following equations for throat pressure, temperature or velocity ($P_i > P_{crit}$) may be derived:

$$P_t = P_i\left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} = .533\ P_i \text{ for } k = 1.4 \tag{2-14}$$

$$T_t = T_{crit} = T_i\left(\frac{2}{k+1}\right) = .833\ T_i \text{ for } k = 1.4 \tag{2-15}$$

$$V_t = V_{crit} = \sqrt{knRT_t} = 1100 \text{ ft/sec for } k = 1.4,\ t = 60°\text{F} \tag{2-16}$$

where $k = \frac{C_p}{C_v}$, or ratio of specific heats of the real gas mixture, in each case.

Since the larger the mass rate of discharge, the larger the thrust of a rocket motor, it is desirable that rocket motors be operated above P_{crit}. Thus, for "nozzling," from (2-14), the critical pressure ratio becomes,

$$\frac{P_i}{P_{atm}} > \left(\frac{k+1}{2}\right)^{\frac{k}{k-1}} \qquad (2\text{-}17)$$

For optimum thrust conditions, chamber pressures are at least several hundred pounds per square inch, and "nozzling" is always easily met. Using (2-12), (2-14), (2-15), and (2-16), $\dot{m}$, the mass rate of discharge, may be expressed in terms of the chamber temperature, pressure, and dimension. Thus,

$$m = \rho_t A_t V_t$$

where

$$\rho_t = \frac{P_t}{nRT_t} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \left(\frac{2}{k+1}\right)^{-1} \left(\frac{P_i}{nRT_i}\right)$$

$$= \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \frac{P_i}{nRT_i} \qquad (2\text{-}18)$$

and

$$V_t = \sqrt{k}\left(\frac{2}{k+1}\right)^{1/2} \sqrt{nRT_i}.$$

By substitution,

$$\dot{m} = \left[\frac{2}{k+1}\right]^{\left(\frac{k+1}{2(k-1)}\right)} \sqrt{\frac{k}{nRT_i}} \left(A_t P_i\right), \qquad (2\text{-}19)$$

or setting all the terms on the right-hand side (except $A_t P_i$) equal to C_m,

$$\dot{m} = C_m A_t P_i \quad \text{or} \quad \dot{W} = C_w A_t P_i \qquad (2\text{-}20)$$

where C_m is defined as the mass discharge coefficient and C_w is the more generally used term, weight flow coefficient. The mass rate of discharge, then, is proportional (in any given system) to only two variables: the chamber pressure and the throat area.

Other useful performance criteria include:

Thrust coefficient,

$$C_F = F/P_i A_t = C_m I_{sp},$$

where F = total thrust, lb

Characteristic velocity,

$$C^* = V_j / C_F$$

Total impulse-weight ratio,

$$R_i/W = \frac{F\Delta t}{W_{total\ rocket}} = \frac{I_{sp} \cdot W_{propellant}}{W_{total\ rocket}}$$

2-6 NOZZLE DESIGN

Since thrust from a rocket motor is proportional to the momentum of the exhaust gases ejected per second, and since momentum is equal to mass times velocity, the efficiency or thrust could be increased at no extra cost in fuel consumption if the exhaust velocity could be maximized. The means of doing this was first demonstrated by a Swedish engineer, Carl G. F. deLaval, by the design of a convergent-divergent nozzle. Before his discovery, engineers always attempted to obtain supersonic velocities by a convergent nozzle. As was shown in Par. 2-5, if such a nozzle is used and the pressure in the chamber of the motor is increased, a point will be reached where the velocity of the gas at the throat will reach a critical value, the maximum of which is the velocity of sound in the gas. Of course, the velocity of sound in the rocket exhaust is about three times that in ordinary air (about 1100 ft/sec) since the speed of sound in a gas increases with the temperature and with R. However, as indicated above, the use of a convergent nozzle puts a definite limit on the velocity that can be obtained and that velocity cannot be exceeded no matter how high the pressure in the chamber is raised.

The relationships between change in channel cross section area, A, and the resulting change in speed, V, for a compressible fluid are embodied in a consideration of isentropic flow of a compressible fluid in a channel of varying cross section. The momentum equation, written in differential form, is

$$VdV + \frac{1}{\rho}\,dP = 0 \qquad (2\text{-}21)$$

Continuity considerations prescribe density relationships,

$$\frac{d\rho}{\rho} + \frac{dV}{V} + \frac{dA}{A} = 0 \qquad (2\text{-}22)$$

Referring to the differential expression for the velocity of sound in a compressible fluid,

$$\frac{dP}{d\rho} = a^2. \qquad (2\text{-}23)$$

Combining equations (2-21) and (2-23),

$$VdV + a^2 \frac{d\rho}{\rho} = 0$$

and eliminating $d\rho/\rho$,

$$\frac{dV}{V}\left(\frac{V^2}{a^2} - 1\right) - \frac{dA}{A} = 0$$

$$\text{or } \frac{dV}{V}(1 - M^2) = -\frac{dA}{A} \qquad (2\text{-}24)$$

which can be expressed in the form,

$$\frac{1}{k}(M^2 - 1)\frac{dP}{P} - \frac{dA}{A} = 0. \qquad (2\text{-}25)$$

Thus,

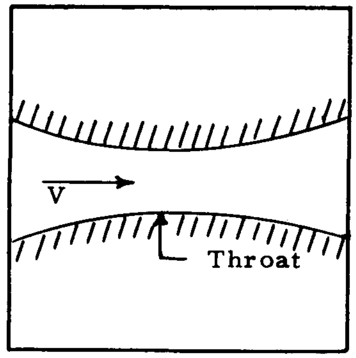
$$\frac{dV}{V}(1 - M^2) = -\frac{dA}{A} = \frac{1}{k}(1 - M^2)\frac{dP}{P}. \qquad (2\text{-}26)$$

At very low speeds ($M < 1$) the familiar incompressible fluid is valid: a decrease in area produces an increase in speed. Density changes are negligible.
Rewriting (2-22) as,

$$\frac{d\rho}{\rho} = -M^2 \frac{dV}{V} \qquad (2\text{-}27)$$

then, for $M > 1$, the situation is reversed. Density, ρ, decreases rapidly for a given speed increase, so that the channel area A, must increase as speed rises. The higher M, the greater the density change for a speed change. From (2-26), as $dA/A \rightarrow 0$, (a condition at a nozzle throat section) either $M = 1$ or $dV/V = 0$. Thus, "nozzling" is specified, as indicated above.

In summary, the conditions justified by (2-26) and (2-27) are as follows:



Condition		Effects	
$M < 1$,	$dA/A < 0$	$\frac{dV}{V} > 0$,	$\frac{dP}{P} < 0$
$M > 1$,	$dA/A > 0$	$\frac{dV}{V} > 0$,	$\frac{dP}{P} < 0$
$M < 1$,	$dA/A > 0$	$\frac{dV}{V} < 0$,	$\frac{dP}{P} > 0$
$M > 1$,	$dA/A < 0$	$\frac{dV}{V} < 0$,	$\frac{dP}{P} > 0$

In a practical design this phenomena creates design problems. Consider a deLaval nozzle of any inlet pressure P_c, but with a variable discharge pressure P_0. If the discharge pressure is only marginally less than the inlet pressure, the nozzle functions, not as a nozzle, but only as a venturi. This performance is shown on curve *a* on Figure 2-3.

As the discharge pressure is decreased well below the inlet pressure, a point will be reached where a critical pressure P_{crit}, occurs at the minimum cross-sectional area, but the diverging section smoothly diffuses the flow back at subsonic velocity to the discharge pressure. This condition is shown by curve *b*. Further decrease in the discharge pressure with a well designed nozzle will smooth flow after the throat into a supersonic rate of flow as is shown in curve *c*. For discharge pressure between *b* and *c*, supersonic flow will continue for some distance, but in order to satisfy the continuity of flow requirements for discharge of the fluid at exit pressure, a flow discontinuity will occur. This causes a shock wave within the divergent section of the

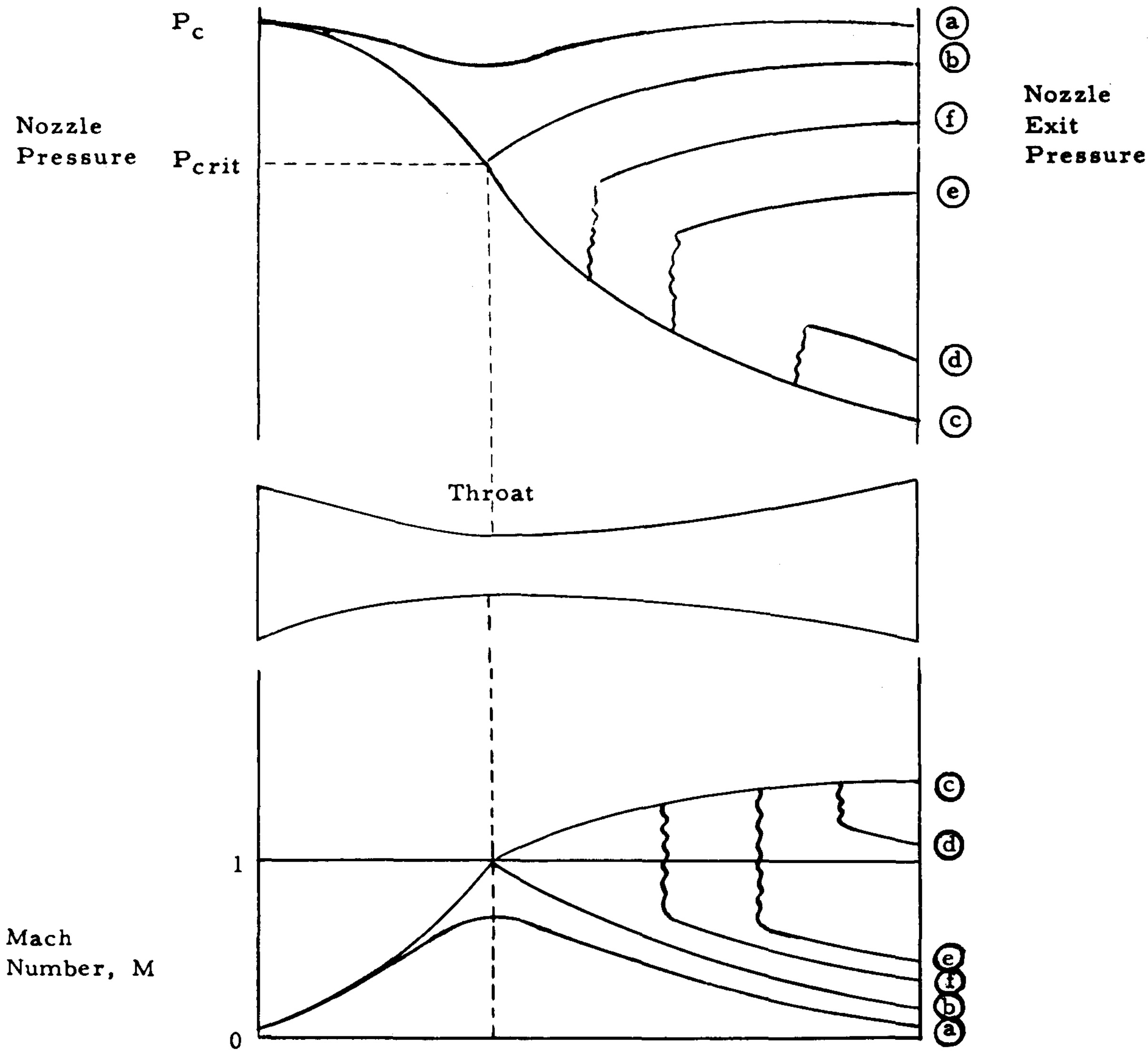


Fig. 2-3 Distance along nozzle.

nozzle. This discontinuity causes a rise in pressure, temperature, and entropy. If the discharge pressure is near the design pressure, the shock wave will occur nearer the nozzle exit as in curve *d*, supersonic velocity is maintained, although the velocity decreases sharply across the wave front; if it varies widely from the design pressure it will occur nearer the throat as in curves *e* and *f*. If the discharge pressure is too high, supersonic velocity may degenerate into subsonic velocity across the shock wave. This is shown in curves *e* and *f*. The losses in a smoothly converging and diverging nozzle, where shock waves are avoided, are small.

Thus, in a well-designed divergent section or expanding cone, a means exists of increasing the exit velocity up to 3 or 4 times that which was obtained at the throat. Although the mass flow at the throat remains constant, the velocity of exit has increased as a result of the decrease in exit pressure (Figure 2-4).

The contour of the exhaust nozzle is usually built up of straight line entry and exit portions connected by a circular arc in the throat section. Since nozzle cooling is difficult, an effort is made to minimize the surface area exposed to the hot

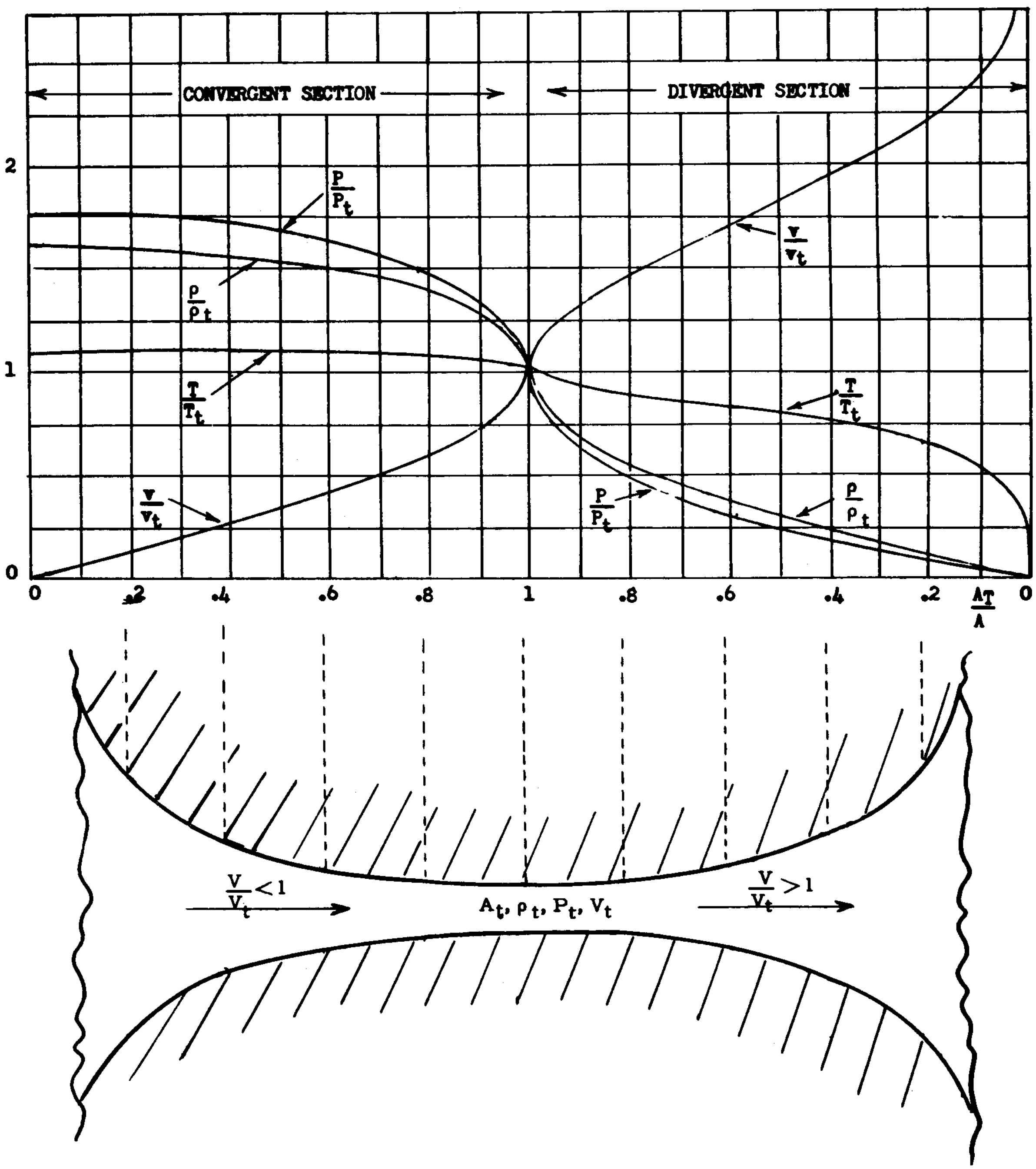


Fig. 2-4 The distribution of pressure, density, temperature and velocity along the nozzle. (Note: subscript (t) signifies parameter at throat; P = pressure; V = velocity; ρ = density; T = temperature; A = area.)

gases. This is accomplished by making the angles α and β (see Figure 2-1) as large as possible in order to reduce the length of the nozzle. However, a loss in thrust accrues from the divergence of the exit section of the magnitude given by the factor λ. Compromises must therefore be made in order to arrive at a nozzle shape that can be satisfactorily cooled and, at the same time, deliver maximum thrust.

2-6.1 SUMMARY OF REACTION MOTOR PERFORMANCE CRITERIA

Reaction motor basic performance factors are summarized as follows:

2-6.2 NOZZLE CONFIGURATION

The combustion process in a reaction motor produces large volumes of gases at high pressures and temperatures. To exhaust them at these high temperatures would mean a considerable waste of potential energy. A nozzle (Figure 2-1) converts the heat energy of the exhaust gases to kinetic energy by expanding and cooling them as they flow through the nozzle. In the divergent section of the nozzle, the exhaust gases experience a further acceleraton in being expanded, with a resulting further creation of momentum and thrust. The design of an efficient nozzle is a complex task. The throat area (A_t), the exit area (A_e), the entrance angle (β), exit angle (α) are all critical. Their ideal value will vary with different operating conditions of motor pressures, temperatures, etc. Improperly designed entrance and exit angles will cause shock waves and turbulence in the exhaust jet, with resulting loss of exhaust velocity and motor thrust. As an ideal, the nozzle should expand the exhaust gases down to atmospheric pressure in order to extract the maximum possible heat energy. Should over-expansion occur, that is, when the exhaust gases are expanded to pressures below atmospheric, shock waves will occur in or near the nozzle exit with resulting loss of exhaust velocity and motor thrust.

2-6.3 ENTRANCE AND EXIT ANGLES

The conventional exhaust nozzle consists of a converging and diverging section. What angles of convergence and divergence should be used for best performance? It is known that the flow of gases should follow streamlines, or the contour of the nozzle, since separation and turbulence are accompanied by excessive drag. Therefore, the entrance and exit angles will have practical limits if the gas is to flow along the contours of the nozzle. The overall length of the nozzle, which is a function of the entrance and exit angles, will merit consideration for such practical reasons as weight, drag, permissible size, and cost. In Figure 2-1, β is ordinarily on the order of 30°, while an α of near 15° seems to be optimum. It can be seen that for a given chamber and throat diameter, the length of the nozzle is a function of α and β. Separation takes place when α exceeds approximately 40°. Therefore, α should always be less than 40°.

2-6.4 NOZZLE ANGLE CORRECTION FACTOR

It is apparent that the thrust component upon which performance calculations are based is the component along the longitudinal axis of the motor. However, the exhaust gases leave the nozzle in a conical section. The exhaust velocity should be reduced to its horizontal component which is λV_e, where λ is the nozzle angle correction factor. The parameter λ is dependent upon α and has been found mathematically to be equal to $\frac{1}{2}(1 + \cos\alpha)$. Typical values for λ range from 0.96 to 0.98. The velocity thrust component equals $\lambda \dot{m} V_e$.

2-6.5 OVEREXPANSION AND UNDEREXPANSION

It is often assumed that gases are expanded by nozzles to precisely atmospheric pressure, or $p_e = p_o$. Although it is theoretically desirable that $p_e = p_o$, in the actual case, the exhaust pressure will not always equal the atmospheric pressure. The exhaust gases, in all probability, will be either slightly overexpanded or underexpanded (Figure 2-5). In practice it has been found that when the exhaust gases have been expanded to a pressure which is on the order of a few pounds per square inch less than atmospheric, oblique shock waves will form. Across each of these shocks a little pressure will be recovered until eventually p_e will equal p_o. Therefore shock waves prohibit overexpansion beyond a certain point. In the case where the gases reach the exit section of the nozzle in an under-

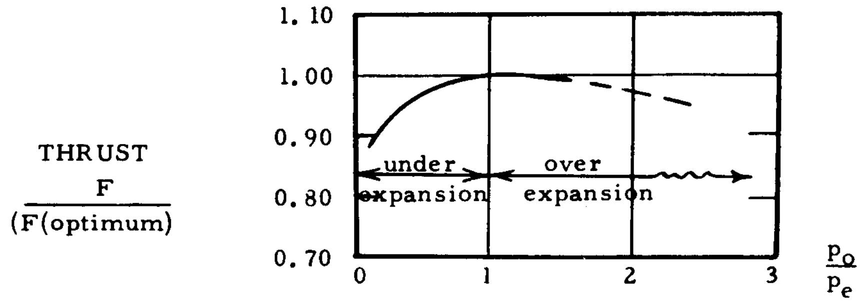
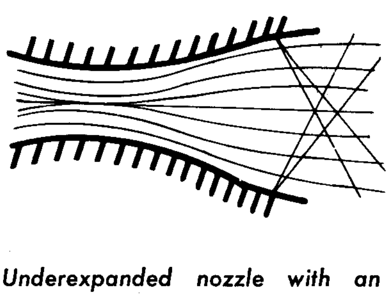


Fig. 2-5 Effects of underexpansion and overexpansion on nozzle performance.

expanded condition, or $p_e > p_o$, expansion will continue in the surrounding medium until the pressures are equal.

(a) Underexpansion: ($p_e > p_o$). An underexpanding nozzle is one which discharges fluid at a pressure greater than the external pressure, p_o, because exit area is too small. The expansion of the fluid is therefore incomplete within the nozzle and continues outside. F_p in this case will be positive and tend to increase F; however, F_r will be less than it would be if p_e were equal to or less than p_o because potential energy is not converted to exhaust velocity. Most rocket motors in common use operate under conditions of underexpansion, particularly when launched from the ground for flight at high altitudes (surface to air missiles). A further illustration is the variation in performance of air-to-air missiles with altitude which is attributed to this characteristic of nozzle performance.



Underexpanded nozzle with an expansion shock forming at nozzle exit.

(b) Overexpansion: ($p_e < p_o$). An overexpanding nozzle is one in which the fluid is expanded to a lower pressure than the external pressure. It has an exit area which is too large. F_p in this case will be negative and will tend to decrease F; however, F_v increases as p_e decreases. Overexpansion is characterized by the formation of shock waves inside and outside the nozzle. (See lines *e* and *f* Figure 2-3.)

The different possible flow conditions in a divergent nozzle section are:

(a) When the external pressure p_o, is below nozzle pressure p_e, the nozzle will flow full but will have expansion (tensile shock) waves at its exit section (underexpansion).

(b) For external pressure p_o, slightly higher than pressure p_e, the nozzle will continue to flow full ($p_e \geq 0.4P_o$). Oblique shock waves exist outside the exit section.

(c) For higher external pressure, a separation of the jet will take place in the divergent section of the nozzle. The separation is axially symmetrical and is accompanied by normal or oblique shock waves. As external pressure increases, the point of separation travels upstream. Further, the area of the jet contracts to preserve continuity (overexpansion). A net loss of thrust occurs.

(d) For nozzles in which the exit pressure is very close to the external pressure, supersonic flow prevails throughout the nozzle (line *c*, Figure 2-3). The nozzle is operating at design point.

(e) Properly expanded, $p_e = p_o$. F_p is now equal to zero. Therefore $F = F_r$. This is the maximum thrust that can be obtained by a particular rocket at its designed altitude, where $p_e = p_o$. Thus, it is desirable from the standpoint of thrust, to have p_e always equal p_o. This, however, is impossible for rockets of fixed dimensions which operate throughout a wide range of altitudes and corresponding pressures.

2-6.6 EXHAUST VELOCITY

The basic thermodynamic relationship for exhaust velocity, V_e, based on isentropic flow above the critical pressure ratio is,

$$V_e = \sqrt{\frac{2k}{k-1}\left(\frac{p_i}{p_i}\right)\left[1 - \left(\frac{p_e}{p_i}\right)^{\frac{k-1}{k}}\right]}$$

Using perfect gas law relationships, this may be rewritten as,

$$V_e = \sqrt{\frac{2gk}{k-1} R^1 T_i \left[1 - \left(\frac{p_e}{p_i}\right)^{\frac{k-1}{k}}\right]}$$

$$= \sqrt{\frac{2gk}{k-1} R^1 T_c \left[1 - \left(\frac{p_e}{p_c}\right)^{\frac{k-1}{k}}\right]} \qquad (2\text{-}28)$$

where T_c and p_c refer to chamber (or stagnation) conditions. Thus,

$$V_e = \sqrt{\frac{2gkRT_c\eta}{(k-1)\,M}}$$

where

$$\eta = 1 - \left(\frac{p_e}{p_c}\right)^{\frac{k-1}{k}}$$

the ideal cycle efficiency of constant pressure engine cycle operating between pressures p_c and p_e, and the gas constant R^1, for the fluid, is replaced by the universal gas constant R, divided by the average molecular weight of the fluid (exhaust products) M.

Since $V_e \sim \sqrt{\frac{T_c}{M}}$, the greatest promise for high velocity of exhaust and highest velocity thrust lies in use of fuels which offer prospects of highest combustion temperatures (within limits of motor wall strength) and low average molecular weights of exhaust products. The so-called "new," "exotic," or "zip" fuels described in Part 1 (Sources of Energy) are specifically tailored to meet this criterion. Fuels containing free radicals offer great promise in this area. Such fuels of fluorine and boron compounds, now under engineering development, offer specific impulse ratings in excess of 400 seconds, in comparison with present standards of 350 seconds for liquid propellants and 220 to 280 seconds for solid propellants. For outer space travel, the same criterion is the basis for solar, nuclear, and ionic propulsion systems with promises of specific impulse ratings in excess of 1800 seconds.

2-7 SOLID PROPELLANT ROCKETS

The simplest of reaction motors in design is the solid propellant rocket motor. It is easy and inexpensive to construct. In this type of rocket the combustion chamber contains the solid propellant. Ballistite in stick form or cast Thiokol might be used in a typical case. Ignition of this charge by an igniter causes rapid burning and the rapid liberation of hot gases. Rockets of this type generally have high specific propellant consumption and deliver great thrust but generally of only short duration. Internal pressures are often high.

For instance, ordinary solid propellants require pressures up to 2000 psi in order to sustain combustion, and the exhaust gas temperatures reach 4000 to 5000°F. These high pressures and temperatures necessitate relatively thick motor walls to contain them. Solid propellants are susceptible to temperature extremes. This is particularly true of ballistite. At high temperatures (over 150°F), the grain may become plastic and at low temperatures (below 20°F), the grain may become brittle. Either of these conditions may cause erratic burning or explosion, since at higher temperatures they burn more rapidly, and when brittle, they break with resulting increases in initial burning surface. Recent development has appreciably improved this temperature sensitivity.

Since a solid propellant rocket requires a relatively heavy casing, the ratio of the weight of the propellant to the total weight of the rocket is low, approximately 0.7. To obtain long ranges and to carry large pay loads, a large percentage of the total weight of the rocket must be propellant. Recent developments of internal burning grains with a slow rate of burning and low operating pressures should help to overcome these undesirable features. Solid propellant rockets have in recent years shown increasing promise for use

in long range missiles.

In summary, the general characteristics of solid propellant rockets are:

(a) Very simple design.

(b) Ready to fire on short notice.

(c) Propellant tends to deteriorate at temperature extremes.

(d) Combustion chamber is propellant container and so must be large.

(e) Relatively short burning times (.05 to 40 seconds).

(f) No control over rate of burning during flight.

2-7.1 GRAIN GEOMETRY

In order to attain the desired mode of burning, many grain forms have been studied and used (several are shown in Figure 2-6). Broadly speaking, solid propellant rockets may be classified in their burning into two classes: restricted and unrestricted.

In the restricted burning rocket, the propellant charge is often made in the form of a solid right circular cylinder. The cylindrical side surfaces and one end face are inhibited or restricted from burning by a suitable lining or coating, and burning is allowed to proceed from one end only. This type of rocket is sometimes called "end burning" or "cigarette" burning. The duration of thrust obtained from a restricted burning rocket is roughly proportional to the length of the charge and depends upon the chamber pressure and the type of propellant used. The thrust obtained from such a rocket is proportional to the area of the circular burning surface and depends upon the chamber pressure, the type of propellant and the quality of design.

In the unrestricted burning rocket the propellant charge is often in the form of a hollow right circular cylinder. This charge is held in place by a suitable support, grid, or trap, but is uninhibited except for the few support points required to mount it. The charge is ignited and allowed to burn on all surfaces with no attempt made to restrict the burning. The thrust from such a unit is proportional to the burning surface and depends upon the chamber pressure, the type of propellant used, and the design of the rocket unit and powder grain. The duration is proportional to the thickness of the cylindrical wall (web thickness) and depends upon the chamber pressure, the type of propellant, and the internal geometry of the combustion chamber and powder grain.

Most of the other successful designs are but adaptations of these two extremes of charge design. The charges shown on the upper left in Figure 2-6 are usually unrestricted, the two charges on the upper right hand side are restricted burning and semi-restricted burning, respectively.

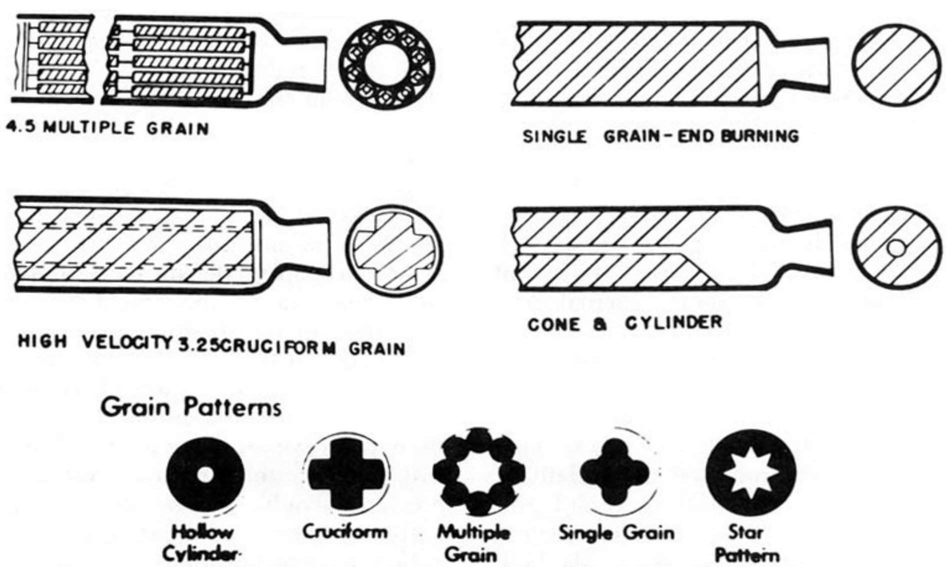


Fig. 2-6 Geometry of some rocket solid propellant charges.

2-8 SPECIAL CHARACTERISTICS OF THE SOLID PROPELLANT ROCKET

There are some special characteristics of solid propellant rockets which should be explained in order to fully understand the major limitations of the rocket propellants now in use. These characteristics are:

(a) Mode of burning.
(b) Temperature sensitivity and limits.
(c) Combustion limit.
(d) Pressure limit.
(e) Physical changes in storage.

The significance of each of these terms will be discussed below.

2-8.1 MODE OF BURNING

In describing a rocket assembly containing a solid propellant, it is not sufficient to refer only to the propellant compostion to determine its characteristics. Information must also be given as to the manner in which the fuel burns under a given set of conditions established to give the desired performance. For rocket propellant calculations, the rate at which the surface of the propellant recedes in a direction normal to itself during the burning, is designated as the rate of burning and is usually expressed as inches per second. The burning rate is dependent upon the chamber pressure and increases as the pressure increases. The range of burning rates at pressures of 2000 psi for modern solid propellants varies between the limits of 1 to 2 inches per second.

A comparison between the pressure-time relationship in a gun and in a rocket will assist in understanding the pressure problem. In the case of a cannon, the pressure within the gun chamber rises very rapidly to a peak pressure of approximately 36,000 psi and, as the projectile travels down the bore of the gun, the pressure falls off quite rapidly. The time interval between the zero points of pressure is of the order of a few milliseconds. Generally, a change in ballistic performance of a cannon propellant is limited to minor changes in dimensions. This is due to the fact that in most instances both the weight of projectile and gun are fixed so as to prevent major changes in propellant design from being effective. Rockets, on the other hand, are somewhat more versatile and permit major changes in propellant design and minor changes in motor design to give the desired performance.

Ideally, the time-pressure curve in a rocket motor should be rectangular; a "plateau" is about the best shape attainable. A typical time-pressure relationship of a rocket is shown in Figure 2-7. The initial pressure rise within the motor chamber may be comparatively slow. Once having reached its peak, it is maintained at a constant level of the order of 1000 to 5000 psi over an appreciable length of time, or at least falls off only very slowly until the charge is completely consumed. The order of time varies from a few seconds up to a minute or more. The limitaticns upon the maximum pressure are governed by the strength of the rocket tube and the maximum mass rate of discharge which can be permitted for a given end use. The pressure within the rocket can be readily changed by changes in propellant composition as well as burning surface. The lower and upper limits in pressure are governed by propellant characteristics which will be discussed later.

2-8.2 TEMPERATURE SENSITIVITY AND LIMITS

The rate at which a solid rocket fuel burns is markedly affected by thetemperatureof the fuel. This change in the burning property will vary with each formulation and even, though to a lesser degree, with the form of grain. To design a rocket motor properly a knowledge of the change in burning rate with temperature must be available to the designer.

If a series of identical rockets are fired after being conditioned at various temperatures, it will be found that as the conditioning temperature is increased above normal (70°F), the pressure obtained within the rocket motor, when it is fired, increases; and as the temperature of conditioning is lowered, decreased pressures are obtained. Since, all other things being equal, the rate of burning is dependent upon the pressure

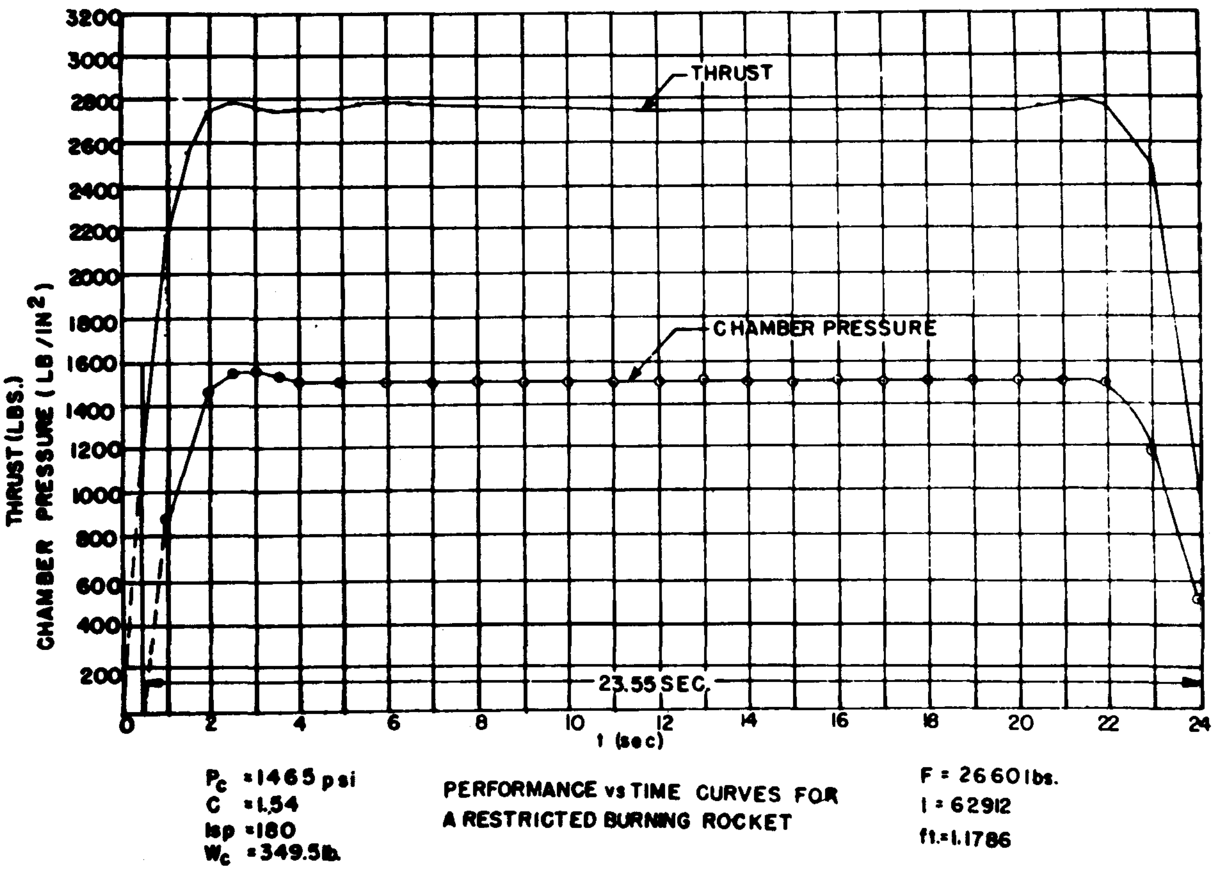


Fig. 2-7 Time-pressure and thrust-pressure relationships of a restricted burning rocket.

within the rocket chamber, it may be stated that the rate of burning varies as a function of temperature. Figure 2-8 shows the actual pressure-time curves of a 3.25-inch rocket fired at various temperatures.

Excessive pressure at high temperatures and brittleness and "chuffing" (see Par. 2-8.3) at low temperatures, limit present solid propellant rockets to a temperature range from about —20 to +120°F.

2-8.3 COMBUSTION LIMIT

Early in the rocket development program, considerable difficulty was encountered in obtaining uniformity of performance of rocket assemblies. As a result of a number of experimental firings it was noted that, when the exhaust nozzle throat diameter had increased beyond a certain point, erratic chamber pressures were obtained. These pressures fell considerably below the projection of the pressure curve established by the firings made at higher pressures, as illustrated in Figure 2-9. Referring to this figure, the lowest chamber pressure in the normal part of the curve, or the corresponding throat diameter, is called the combustion limit for the propellant. For exhaust nozzle throat diameters below the combustion limit the pressure curve is smooth, but after the combustion limit is reached, the pressure versus throat diameter relation is very erratic and unpredictable (chuffing).

The combustion limits for both ballistite and the composite propellants which are currently under development are near 500 psi at 70°F (ambient temperature). The single-base propellants used in conventional guns have a combustion limit of about 5000 psi and therefore

are not suitable as rocket propellants.

2-8.4 PRESSURE LIMIT

Some propellants may be safely used only at chamber pressures below some critical chamber pressure. If the critical upper chamber pressure is exceeded, the propellant charge seems to burn in a violent and unpredictable manner. For double-base propellants, this pressure limit is greater than 12,000 psi. Some composite propellants have pressure limits of 3000 psi and below, which is a disadvantage in their use in certain applications.

2-8.5 PHYSICAL CHANGES IN STORAGE

Double-base propellants decompose slowly on prolonged storage. Their decomposition is autocatalytic. Diphenylamine is usually added to such propellants to neutralize the catalytic effect of the initial decomposition products. It is inadvisable to store ballistite at 140°F for a period of time in excess of two weeks. Prolonged storage of this material at 120°F is not desirable.

The composite propellants do not decompose chemically during prolonged storage; but in an atmosphere of high relative humidity, the sodium nitrate absorbs moisture and the charge becomes soft and mechanically weak. These propellants must be shipped in moisture tight containers and must not be exposed to moisture before use.

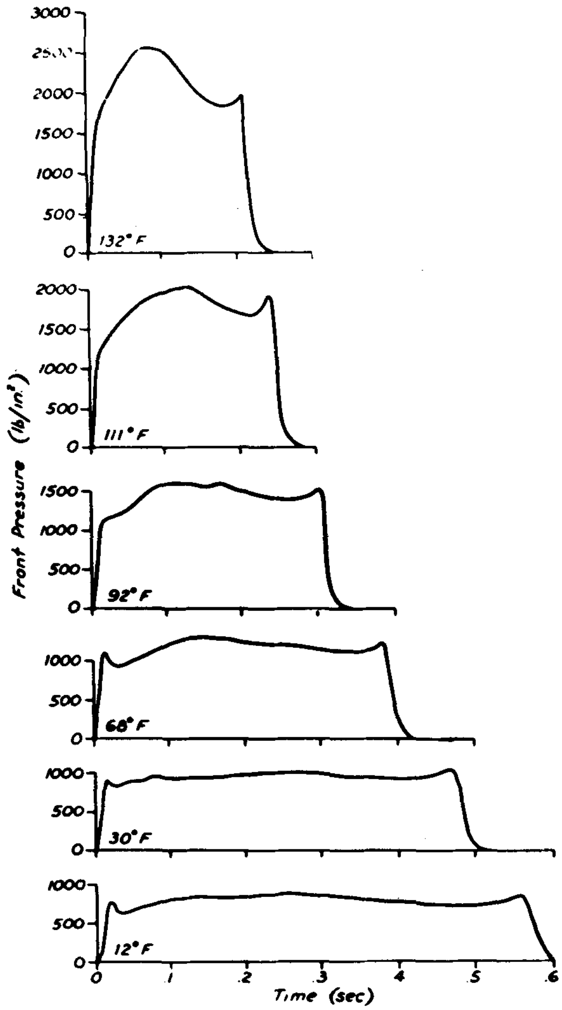


Fig. 2-8 Pressure-time curves for 3.25-inch rocket.

2-9 LIQUID PROPELLANT ROCKETS

Liquid propellant rocket motors have been characterized by long development and "debugging" programs. Much of the costly and time consuming procedure is devoted to the redesign of previously satisfactory hardware in order to eliminate unanticipated "chugging" or rocket motor instability. NACA research in the field of rocket dynamics and controls has indicated that paper designs can be translated directly into successful rocket motors if effects of rocket motor component dynamics are properly considered.

The phenomenon of chugging is one of the most serious problems associated with liquid propellant rockets. Chugging is characterized by severe oscillations in combustion, in the range of 75-300 cycles per second; these oscillations can result in rocket motor failure, missile structural failure, or guidance inadequacy.

A basis for understanding the nature of the instability may be achieved by examination of a simple rocket system consisting of a thrust chamber fed from a large pressurized tank, and having a very short line from the tank to the injector (Figure 2-10).

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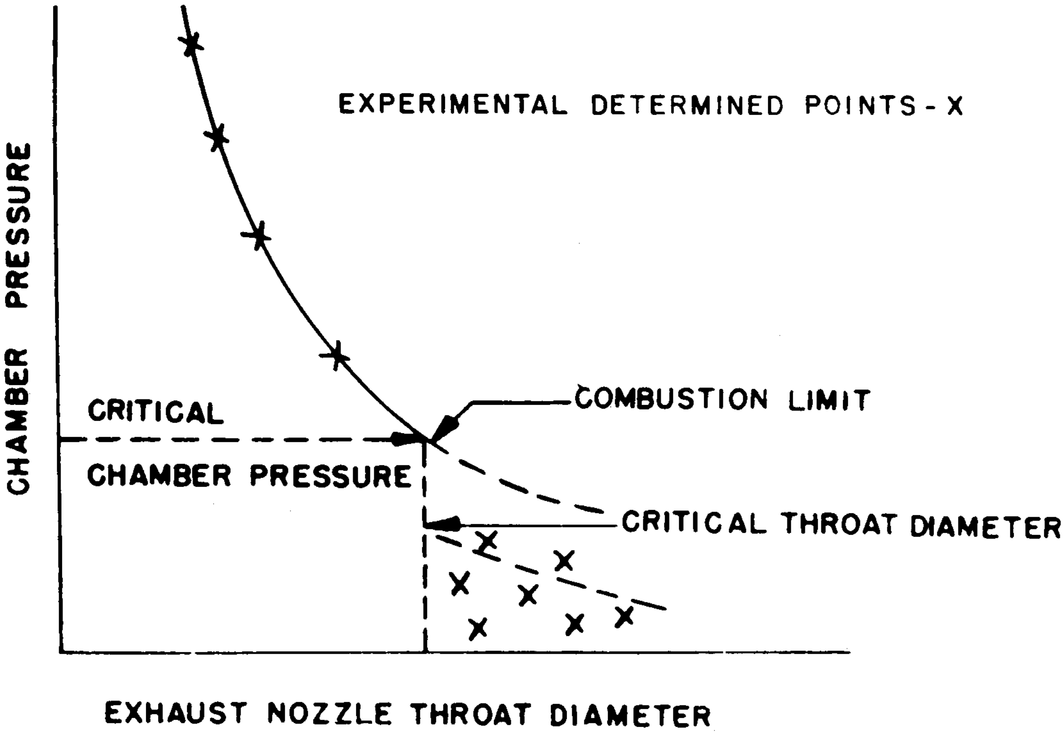


Fig. 2-9 Combustion limit of rocket propellant.

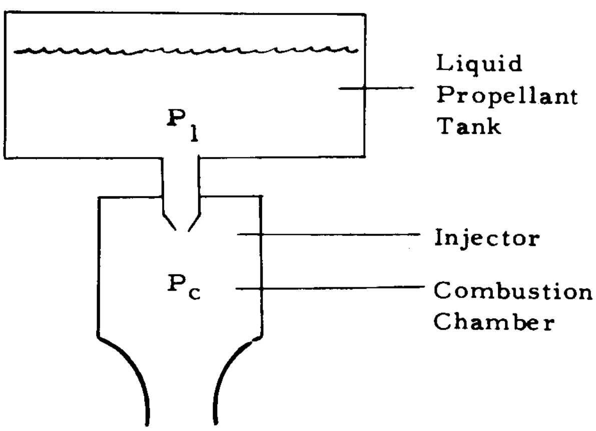


Fig. 2-10 Schematic diagram of a liquid fuel feed system.

In this hypothetical case the pressure P_1, ahead of the injector can be considered constant, but the combustion chamber pressure P_c, and therefore the pressure drop across the injector, can fluctuate rapidly with changes in combustion. Thus, a disturbance in combustion chamber pressure causes a change in the pressure drop across the injector and a corresponding change in propellant flow; the change in propellant flow in turn causes another change in combustion pressure. Consequently, any fluctuations in the combustion chamber pressure are amplified and the system can be unstable. For any specified rocket motor it has been found that increasing the propellant pressure at a fixed combustion chamber pressure can stabilize the system and eliminate chugging. However, the stability has been achieved at the expense of an increase in weight resulting from the heavier pumps and lines that must be used. Furthermore, the same propellant pressure does not necessarily result in stability for a larger or smaller version of the same basic rocket motor.

During an NACA research project, a basic rocket system, consisting of a propellant tank, pipe lines, injector, and combustion chamber, was simulated on an electronic analog computer. It was shown that the dynamic behavior of each component has an effect upon the propellant pressure required for stability. The reason for unsuccessful scaling of rockets to either smaller or larger sizes becomes apparent, as it is shown that component dynamic characteristics do not vary proportionately with size. Proper attention to selection of components can eliminate resonances that lead to instability, and increased

CHAPTER 3

EXTERIOR BALLISTICS

3-1 INTRODUCTION

Exterior ballistics is the science dealing with the motion of a missile from the time it leaves the influence of some projecting medium until it reaches some fixed or predetermined point in space or on the ground.

In a larger sense, understanding this subject from a ballistician's point of view requires a background in physics with emphasis on Newton's laws of motion; mechanics and the analysis of dynamic forces; aerodynamics and the complex forces of air; mathematics, including the calculus; the principle of the gyroscope; and some knowledge of meteorology. The purpose of this chapter is to develop a knowledge of basic ballistic fundamentals leading to a practical conception of what takes place when a projectile is fired from a gun, a bomb dropped from a plane, or a rocket fired from a launcher. With an accurate portrayal of the inertia, gravitational, and aerodynamic forces exerted on a projectile or missile as it moves through the air, the exact calculation of the trajectory, however tedious, poses no serious problem particularly in this era of high speed digital computers which were originally designed to solve the trajectories of projectiles and bombs. The prediction of aerodynamic forces is a matter of considerable difficulty, and thus the primary problem in exterior ballistics now is the accurate and reliable prediction of the aerodynamic forces on new missile designs.

In the development of this basic information, exterior ballisticians rely heavily on highly sensitive model tests and rapid development of engineering applications of compressible flow theory. Wind tunnel tests covering the subsonic region (speeds up to Mach 1), supersonic region (Mach 1 to region of Mach 6), and hypersonic regions (up to Mach 10 is within practical interest) contribute importantly to solving such flow problems (Figures 3-1 and 3-2). Free flight ranges for model tests permit measurement of certain

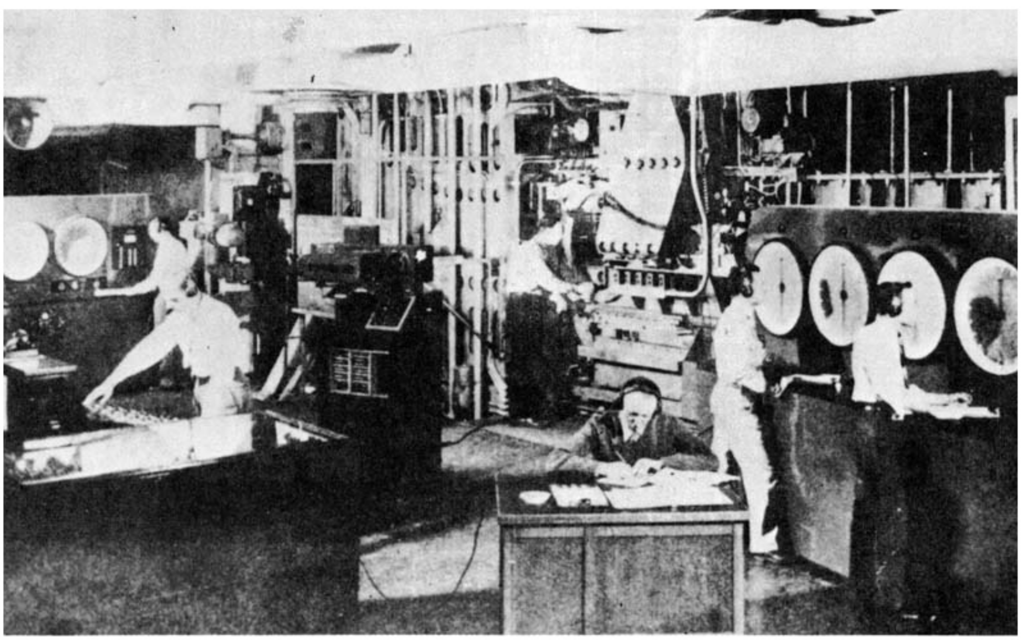


Fig. 3-1 General view of a flexible throat wind tunnel.

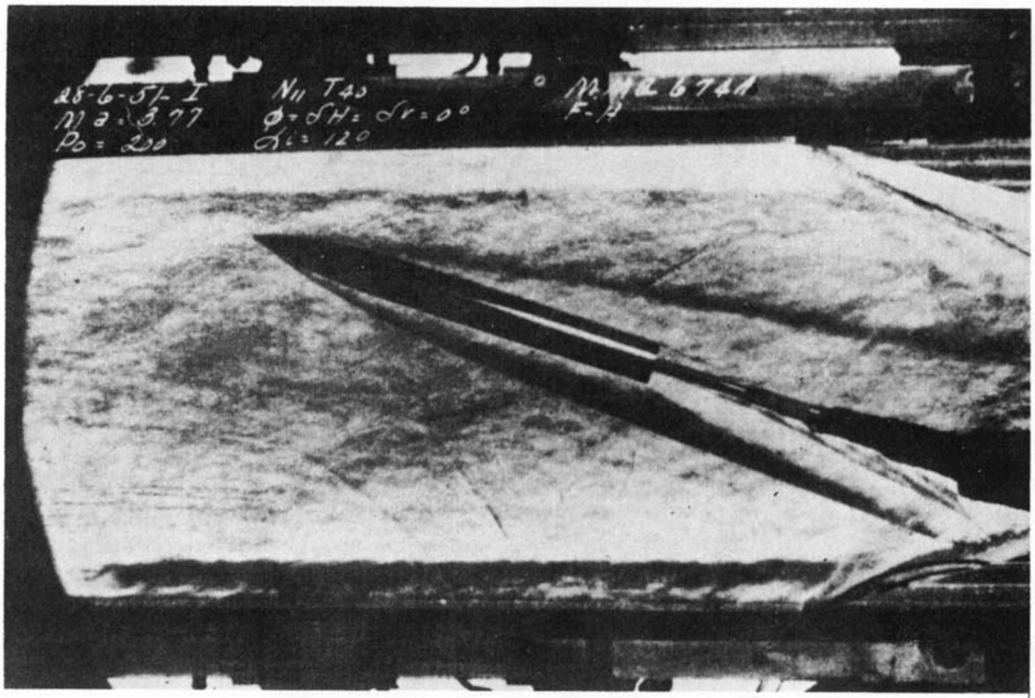


Fig. 3-2 Schlieren photo of model in wind tunnel.

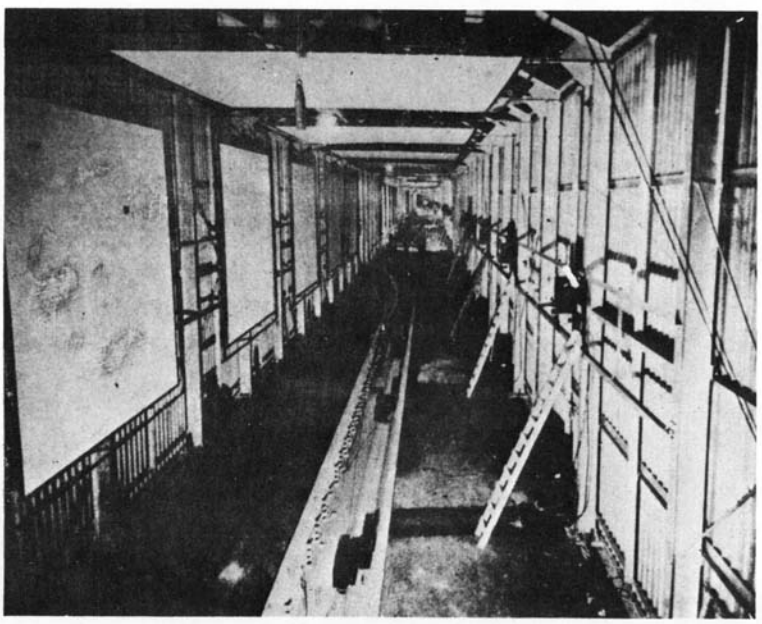


Fig. 3-3 A free flight range.

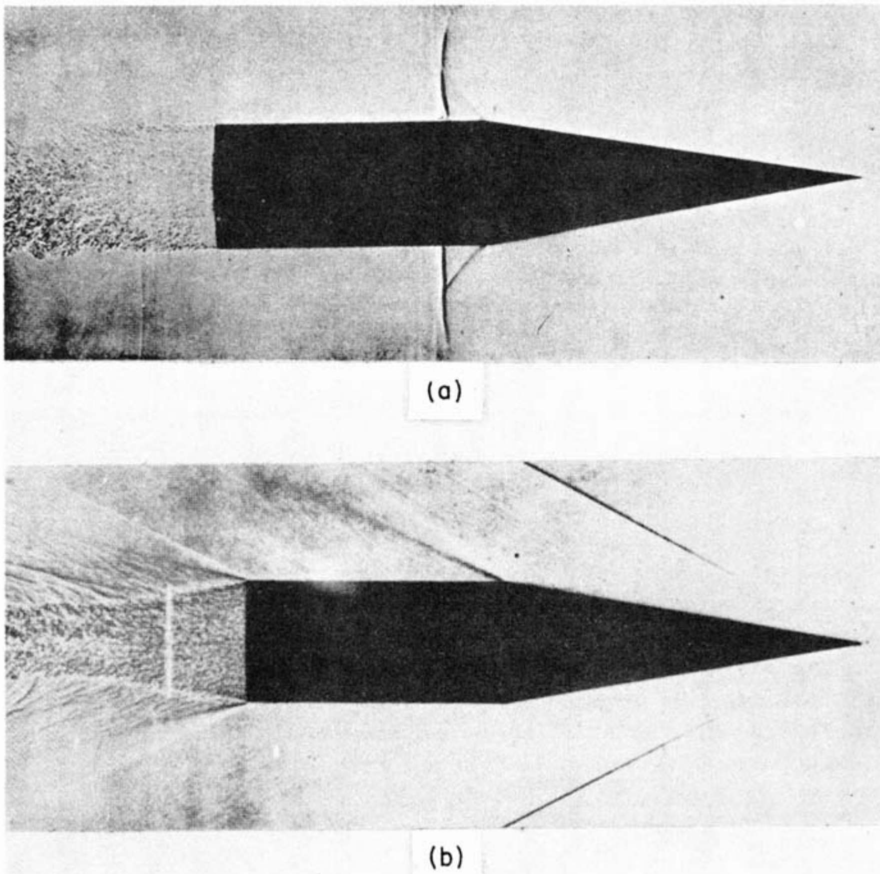


Fig. 3-4 Spark shadowgraphs of 90-mm projectile fired in a free flight range, illustrating (a) normal and (b) oblique shock fronts. Velocity: (a) Mach 0.8; (b) Mach 2.2.

aerodynamic forces which can be measured only with great difficulty, if at all, in wind tunnels. These ranges permit direct tests of flight stability and provide the most accurate measurements of projectile drag (Figures 3-3 and 3-4). Controlled pressure and temperature ranges augment basic research methods for making interferometric determinations of velocity distribution about bodies of revolution. These factors contribute to a basic understanding of spin stabilization and fin stabilization as applied to spinner rockets, optimum bomb and projectile configuration, and fin-stabilized gun-launched projectiles. Fundamental research on boundary layer and heat transfer phenomena in supersonic flight; effects of asymmetry and dynamic balance on projectile accuracy; spin-roll resonance data; factors influencing drag; and aerodynamic consequences of spin on spin stabilized projectiles are vital to the exterior ballistics problems confronting contemporary scientists.

3-2 DESCRIPTION OF A TRAJECTORY

A trajectory may be defined as the curve in space traced by the center of gravity of a projectile in its flight through the air (Figure 3-5). The origin of a trajectory is the position of the center of gravity of the projectile at the instant it is released by the projecting mechanism; the tangent to the trajectory at its origin is the line of departure; the angle this line makes with the

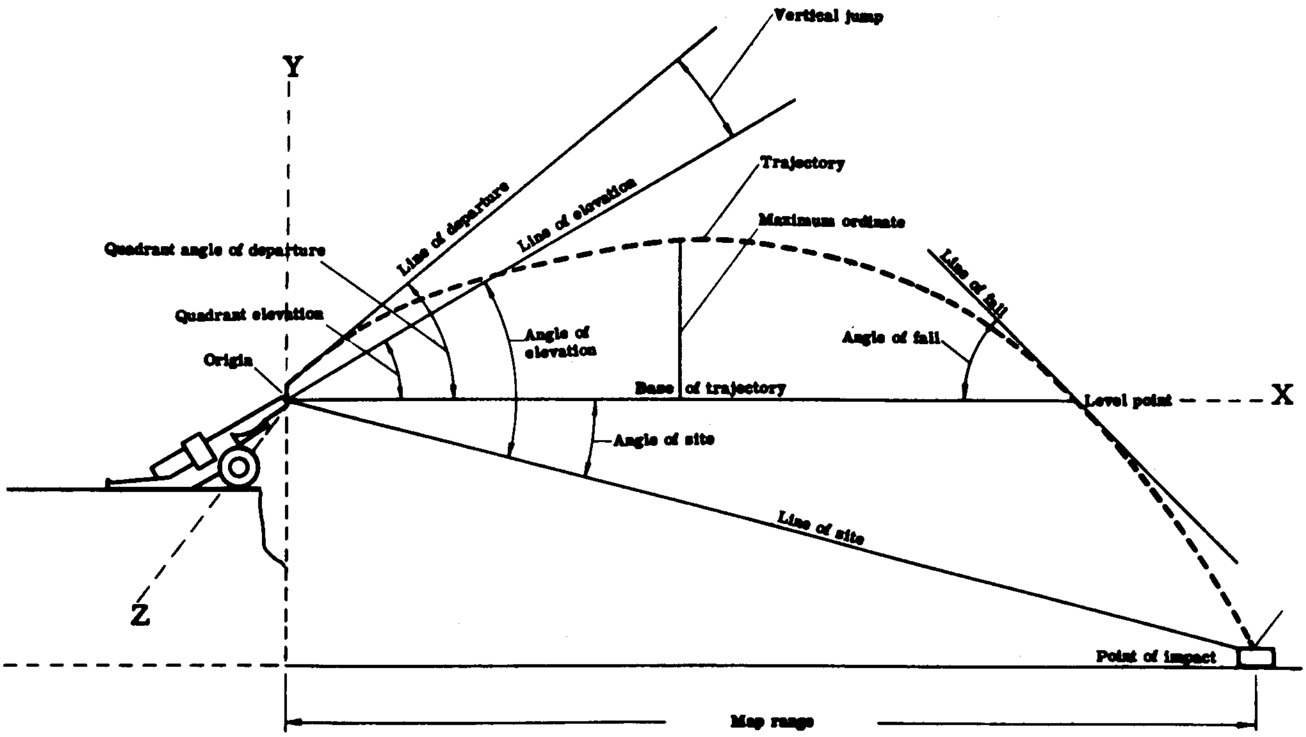


Fig. 3-5 Elements of the artillery trajectory.

horizontal is the quadrant angle of departure. The vertical plane including the line of departure is the plane of departure. In it lie the X (horizontal) and Y (vertical) axes of the coordinate system used in the computation of trajectories, whereas the Z axis lies in the horizontal plane and is perpendicular to the plane of departure. To describe a trajectory completely it is sufficient to specify the x, y, and z coordinates of the center of gravity of the projectile at any time, t (i.e., at every instant), after the release by the projecting mechanism.

The factors which influence the shape of the trajectory of a specified projectile after it leaves the launching device are principally the earth's gravitational field and the characteristics of the air through which the projectile passes. For long range trajectories additional factors must be considered, including the curvature of the earth, the rotation of the earth, and the variation of the gravitational field with altitude. The discussion in this text will be confined mainly to the gravity and air effects. Long range trajectory factors will be covered very briefly.

The design of the projectile and the methods used to stabilize it have a considerable effect on the trajectory. For example, the rotation imparted to a projectile by the rifling in the gun causes it to move out of the plane of departure due to a crosswind force resulting from gyroscopic precession of the projectile nose: The density of a projectile has a direct influence on both its stability and range.

3-3 AERODYNAMIC FORCES ACTING ON THE PROJECTILE

Consider a projectile moving in still air, as shown in Figure 3-6, with its axis making an angle of yaw δ, with the direction of motion. The angle of yaw is defined as the angle between the axis of the projectile and the tangent to the trajectory at the center of gravity of the projectile. The projectile will be acted on by gravity W, acting vertically downward, and an air force

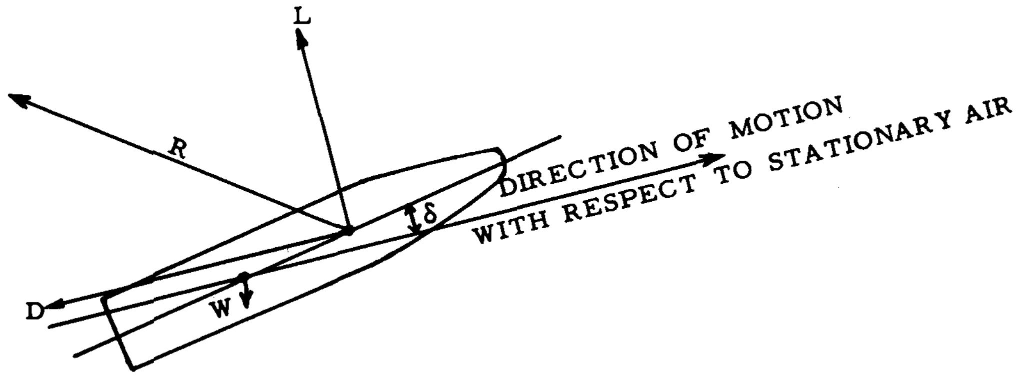


Fig. 3-6 Forces on a projectile moving in still air. Note: Relative position of center of gravity and R is dependent on the manner of stabilization and projectile configuration.

R, which will depend upon the velocity, the characteristics of the air and of the projectile, and upon the presentation of the projectile with respect to the direction of motion. If δ were zero and the projectile symmetrical about its axis, R would point in a direction opposite to the direction of motion. In general, δ is not zero, and thus R intersects the direction of motion. The calculations are simplified by considering R as equivalent to two components, one having a direction opposed to the motion, called the drag or head resistance, and designated by D. The other is perpendicular to the direction of motion, and is designated by L, and called "crosswind force." For a 75-mm projectile moving at a velocity of about 2200 ft/sec with $\delta = 10°$, $D = 150$ lb, $L = 156$ lb, and $R = 216$ lb.

The forces D and L and the angle of yaw δ, are not restricted to the vertical plane as they appear in Figure 3-6. Instead they lie in the plane of yaw (the plane determined by the axis of the projectile and the tangent to the trajectory which intersect at the center of gravity of the projectile). The dihedral angle between the plane of yaw and the vertical plane through the tangent to the trajectory is known as the angle of orientation, ϕ. The motion of projectile about its center of gravity in three dimensions is described in terms of the angle of yaw, δ and angle of orientation, ϕ. The basic equations of motion utilizing the primary aerodynamic forces described thus far are:

$$F_x = m\frac{dv_x}{dt} = -D_x + L_x$$

$$F_y = m\frac{dv_y}{dt} = -D_y + L_y - mg$$

$$F_z = m\frac{dv_z}{dt} = -D_z + L_z$$

The aerodynamic forces acting on a projectile during flight influence the actual path of the trajectory as well as the orientation and velocity of the projectile upon reaching the target. The accuracy of the mathematical analysis depends largely upon the degree of stability with which the projectile flies through the air. The forces described are those of primary significance to a free flight trajectory. A more complete analysis of forces and moments acting on such a projectile follows:

3-3.1 DRAG

The component of the total air resistance which acts in a direction opposed to the direction of motion of the projectile. Drag is made up of three parts: the resistance of the nose; skin friction caused by translation and rotation; and drag on the base (force D, Figure 3-6).

3-3.2 CROSSWIND FORCE

The aerodynamic force which acts in a direction perpendicular to the direction of motion, lies within the plane of yaw, and is proportional to sin δ (force L, Figure 3-6).

3-3.3 OVERTURNING MOMENT

The angular acceleration produced by a couple, the moment of which is equal in magnitude and direction to the moment of R (located at the center of pressure, Figure 3-6) about the center of gravity of the projectile, and is proportional to sin δ.

3-3.4 MAGNUS FORCE

A force which arises from the interaction of the boundary layer of a spinning shell and the wind stream. For a clockwise spinning tennis or baseball, interaction between the wind stream and the boundary layer permits the velocity at the top layer of the surface of the ball to be less than the velocity at the bottom surface, and is thus associated with a higher pressure region. The ball accelerates downward. A spinning projectile, for example, with a counterclockwise angle of yaw in the vertical plane, produces a component of magnus force acting to the left or perpendicular to δ and proportional to spin rate, velocity, and sin δ (Figure 3-7).

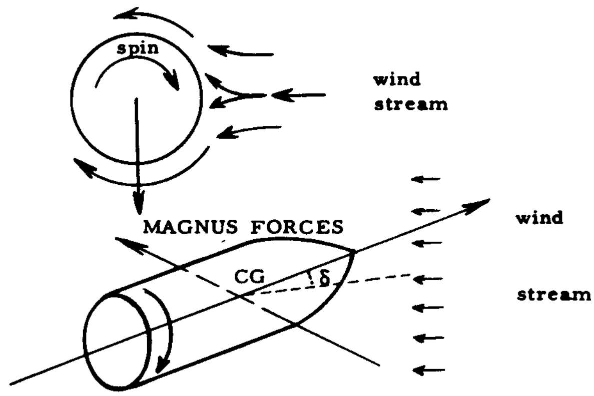


Fig. 3-7 Action of magnus force.

3-3.5 MAGNUS MOMENT

The moment of the magnus force about the center of gravity.

3-3.6 YAWING MOMENT DUE TO YAWING

A torque acting on a rotating projectile, its axis coinciding with the axis of yawing motion and exerting a moment opposing the angular velocity of the axis of the shell.

3-3.7 ROLLING MOMENT

Defined as that torque acting on a rotating projectile opposing spin.

Those forces normally neglected are yawing moment due to yawing, magnus forces due to yawing, and magnus moment due to yawing, the effects being negligible for the majority of trajectories subjected to analysis.

3-4 EVALUATION OF PRINCIPLE AND MOMENTS

For a given projectile shape, the dominant forces and moments acting on a projectile are expressed as follows:

$$\text{Drag, } D = K_D \rho d^2 u^2$$
$$\text{Lift, } L = K_L \rho d^2 u^2 \sin\delta$$
$$\text{Overturning moment, } OM = K_m \rho d^3 u^2 \sin\delta$$

where

d = diameter, ft
ρ = density of air, lb/ft^3
δ = angle of yaw, degrees or radians
u = projectile velocity relative to air, ft/sec

K_D, the drag coefficient (of dominant interest in trajectory determinations) is a function of $\frac{\rho u d}{\mu^*}$ (Reynold's number), $\frac{u}{a}$ (Mach number), and δ. It is normally determined as a function of u/a, and evaluated in terms of δ if δ exceeds 2—3°. (The necessity for investigating the latter is evident when considering the exterior ballistics of a gun-launched projectile or rocket fired from high speed aircraft in a direction that differs from the forward motion of the aircraft.) Examples of standard plots are shown below for two projectile shapes (Figure 3-8).

Although the two curves in Figure 3-8 have substantially the same characteristics there are some marked differences. For example, projectile type A has both a sharp ogive and a boat-tail. A comparison of the two projectiles illustrates

* μ = viscosity, lb/ft sec

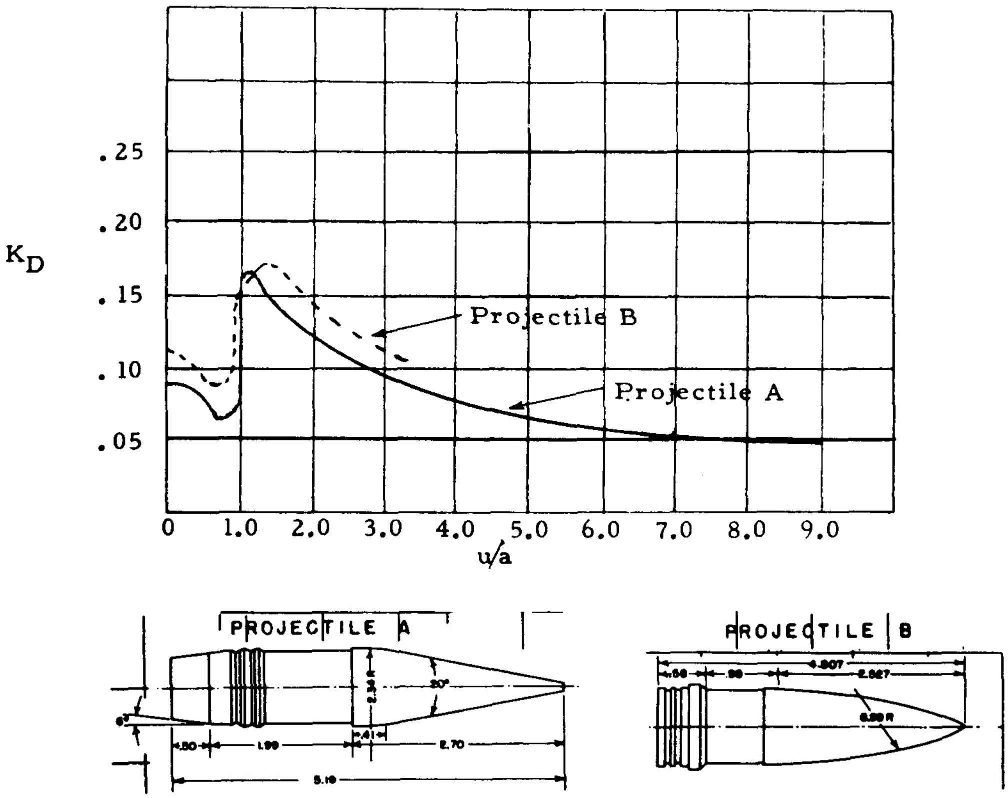


Fig. 3-8 Drag coefficient versus Mach ratio for different projectile shapes.

the fact that sharp ogives are effective in decreasing drag above the speed of sound and boattailing is effective in lowering drag below the speed of sound.

K_L, the lift coefficient, likewise is a function of the parameters, $\frac{\rho u d}{\mu}, \frac{u}{a},$ and δ, as is K_m, the overturning moment coefficient. The magnitude of OM, however, also depends on the position of the center of gravity relative to the center of pressure of the projectile.

While the mathematical statements of these functions are generally specific, the projectile form and drag coefficient (expressed in terms of Mach number) require clarification.

3-4.1 PROJECTILE FORM

The form of a moving projectile determines the way in which air will behave as it flows over the projectile's surface. A pointed projectile encounters less resistance as it penetrates the air at high speeds than a blunt-nosed projectile, and a projectile with a tapered base allows air to flow by it more readily than one with a square base. The drag function used is one based on the shape of the projectile in question and includes a form factor applicable to specific projectile shapes.

3-4.2 DRAG COEFFICIENT

The plot of the drag coefficient against the Mach number for any type projectile will indicate an increase in the value of the drag coefficient as the projectile approaches the speed of sound. The sudden increase in the drag is because local velocities on the surface of the projectile are greater than that of sound, and thus a shock wave is set up. At speeds greater than that of sound, the entire character of the air flow of air is changed. At lower velocities, a projectile is retarded primarily because of the

friction of the air stream slipping over the projectile surface. This produces a skin friction which is usually accompanied by only a slight disturbance at the base of the projectile. As the velocity of the projectile is increased, the air stream is unable to close in behind the base, and a decided turbulence appears behind the projectile. This is known as wake. The projectile is then encountering drag from both skin friction and wake. A further increase in velocity beyond the speed of sound will introduce resistance in the form of shock waves. Therefore, a projectile traveling at supersonic speed encounters retardation, so far as velocity is concerned, which is the combined effect of skin friction, wake, and shock waves. Such characteristics are evident from examination of Figure 3-4 which compares shadowgraphs of a projectile flying at subsonic and supersonic velocities.

3-5 BALLISTIC COEFFICIENT

One of the most important factors which appears in the formal differential equations of a trajectory is called the ballistic coefficient,

$$C = \frac{W}{id^2}$$

where:

W is the weight of the projectile in pounds.
d is the diameter of the projectile in inches.
i is an empirical factor, called the form factor, which compares the "streamlining" (actually the drag coefficient) of the projectile or bomb under consideration, at a given velocity, with that of an arbitrary standard at the same velocity.

The ballistic coefficient indicates the ability of a projectile to overcome air resistance; the larger the value of C the less the retardation. C is commonly thought of as a constant. However, since firing tables and bombing tables are made up from data taken from ballistic tables modified to agree with data obtained from actual test firing, it is expedient to use slightly different values of C for different sections of the trajectory. Representative values of C for various projectile types are given in Table 3-1.

The ballistic coefficient has a pronounced effect on the characteristics of trajectories. The curves in Figure 3-9 show that at relatively low initial velocities, such as those given by the lower zone charges of field howitzers, the loss of velocity due to air resistance is relatively small as compared with that which is produced when the initial velocities are relatively high. Also the effect of the ballistic coefficient increases as the initial velocity increases. It is evident that projectiles to be fired with high initial velocities should be made as heavy as other conditions will permit, and should be given a shape which is aerodynamically as efficient as possible. Figure 3-10 indicates the effect of the ballistic coefficient on projectiles fired with the same velocity and angle of elevation. The great reduction in range for small values of C compared with that obtained in vacuum with $C = \infty$ should be noted.

TABLE 3-1 VALUES OF C FOR VARIOUS PROJECTILE TYPES

Projectile Type and Caliber	Ballistic Coefficient	Form Factor
76-mm H.E.P.	1.15	0.96
105-mm rifle, H.E., A.T.	1.29	0.76
90-mm AP	1.59	1.19
90-mm H.E., A.T.	1.78	1.65
155-mm H.E.	2.056	1.02

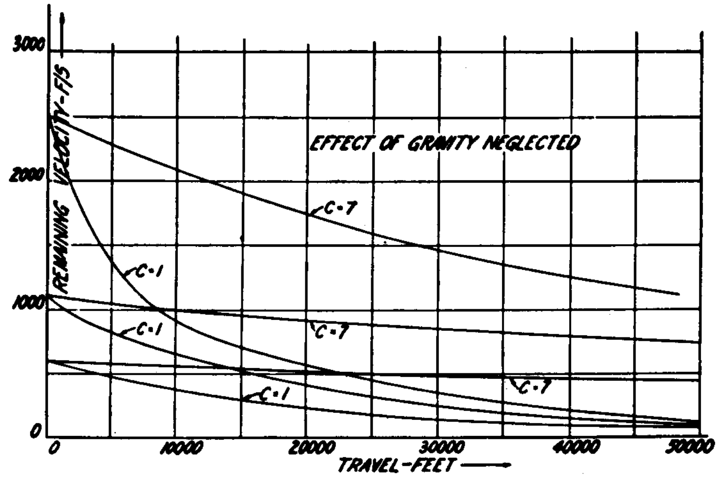


Fig. 3-9 Remaining velocity versus travel.

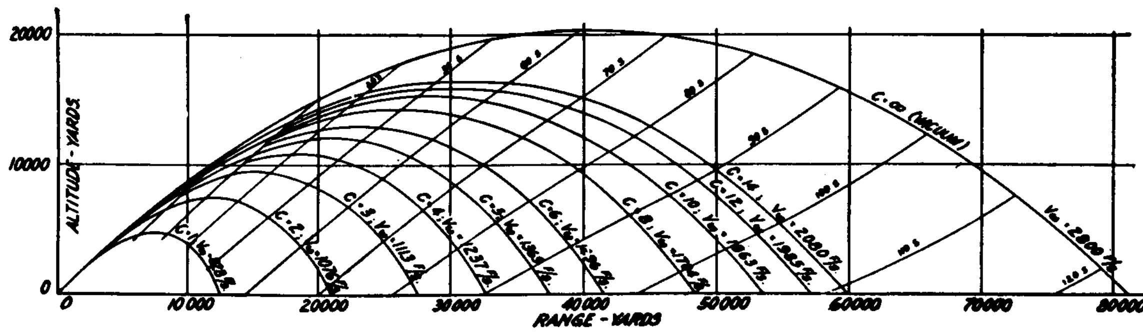


Fig. 3-10 Plots of trajectories (v_0 = 2800 ft per second, θ_0 = 45°; V_ω, terminal velocity, ft/sec; C, ballistic coefficient).

3-6 BALLISTIC TABLES AND FIRING TABLES

To reduce the labor of calculating a trajectory each time such a problem is encountered, ballistic tables have been constructed which contain in condensed form, the results of the computations of a large assortment of trajectories. These tables are of general application but do not apply directly to any projectile. They are based on standard condtions, simplified and idealized to an extent which is physically impossible to attain. Firing tables, on the other hand, apply to particular projectiles. These tables supply the using service with the data required for proper aiming. Data from the ballistic tables are essential in making up firing tables but the latter are predicated on standard conditions which are, individually, physically possible. Wherever practicable, corrections to be applied for variations from these standard conditions are tabulated. The problem for the ballistician, then, is to compile the most accurate data possible, based on theory and experiment, into firing tables to assist the using services to hit the target. The preparation of ballistic tables is a step in this process. A brief excerpt from such a table is given in Table 3-2.

TABLE 3-2 COMPACT BALLISTIC TABLE

Range in Yards for Various Values of θ_0, v_0, and C							
v_0 ft/sec	C						
	2	4	6	8	10	12	14
$\theta_0 = 15°$ 1000	4,105	4,534	4,713	4,816	4,882	4,927	4,961
1500	6,035	7,406	8,204	8,749	9,147	9,453	9,695
2000	7,640	10,163	11,853	13,106	14,061	14,807	15,409
2500	9,167	12,937	15,680	17,809	19,478	20,815	21,909
3000	10,603	15,657	19,548	22,675	25,189	27,237	28,939
$\theta_0 = 30°$ 1000	6,383	7,365	7,799	8,047	8,209	8,321	8,405
1500	8,895	11,351	12,786	13,782	14,522	15,104	15,575
2000	10,756	14,721	17,391	19,431	21,075	22,438	23,591
2500	12,488	18,072	22,207	25,616	28,503	30,961	33,060
3000	14,132	21,436	27,283	32,403	36,862	40,672	43,949
$\theta_0 = 45°$ 1000	7,038	8,305	8,865	9,186	9,393	9,537	9,645
1500	9,798	12,867	14,661	15,888	16,791	17,490	18,051
2000	11,764	16,617	19,874	22,314	24,234	25,803	
2500	13,595	20,384	25,398	29,427	32,793		
3000	15,359	24,288	31,472	37,715			

3-7 TRAJECTORY ANALYSIS

The solution of the trajectory problem has been of extreme academic interest to mathematicians and scientists for centuries and the impossibility of solving it in terms of explicit functions is recognized. No attempt will be made here to develop a complete analysis; however, an appreciation of the problem is of importance in the realization that the differential equations defined are an outgrowth of experience in this field and are developed in terms of factors such as ballistic coefficient and drag coefficient, which are adjusted from an approximation based on aerodynamic studies to an exact value, which permits a mathematical solution to exactly reproduce data obtained from test firings.

Such exact solutions require batteries of skilled computing machine operators to solve the numerous trajectories that are represented in current firing tables and bombing tables used by combat units. The technique of solution, through development of high speed digital computers begun during World War II, has now progressed to a state where the trajectory problem may be solved in a fraction of the actual time of flight of shell.

Figures 3-11 and 3-12 are included in this text in order to outline the approach to production of firing and bombing tables using digital computing techniques. The equations of motion for a particle trajectory with drag and including the effects of wind and the coriolis force due to the earth's rotation are:

$$\ddot{x} = -E\,(\dot{x} - \omega_x) + \lambda_1 \dot{y}$$
$$\ddot{y} = -E\,(\dot{y}) - g - \lambda_1 \dot{x}$$
$$\ddot{z} = -E\,(\dot{z} - \omega_z) + \lambda_3 \dot{y} + \lambda_2 x$$

where

x = downrange distance
y = vertical distance
z = horizontal distance to the right

ω_x, ω_z = components of wind velocity

$\lambda_3, -\lambda_2, -\lambda_1$ = components of angular velocity of the earth

E = resistive functions of the form, $\dfrac{\rho(y)uK_D(M)}{C}$

$g = g_0\left(1 - \dfrac{2_y}{r}\right)$, where g_0 is a constant and r is the earth's radius

C = ballistic coefficient, previously defined

Firing tables are developed on a basis of matching a mathematical solution to the initial and final conditions of an actual firing test:

(a) Conduct test firing of trajectories (up to 150 firings required).

(b) Compute reduction trajectories to determine applicable values of ballistic coefficient, C.

(c) Compute normal trajectories based on standard conditions (up to 3000 required).

(d) Compute variations, where

$\rho = \rho_0 e^{-hy}$ (air density)

$M = M_0 e^{-Ay}$ (speed of sound)

$h = \dfrac{21}{2} A \; (h = 3.16 \times 10^{-5})$

(e) Compute probable errors

Bombing tables are developed on the basis of an accurately measured test trajectory where the drag coefficient can be experimentally determined point by point:

(a) Track bomb fall and measure 6-12 points on each trajectory (10-15 drops required).

(b) Compute reduction trajectories to determine the drag coefficient K_D, and ballistic coefficient C, applicable, where

$$K_D(M) = \frac{M}{d^2\rho\,(y)u^2}\sqrt{\ddot{x}^2 + (\ddot{y} + g)^2 + \ddot{z}^2}$$

(up to 400 required).

(c) Compute normal trajectories with selected K_D and C (up to 600 required) based on standard conditions.

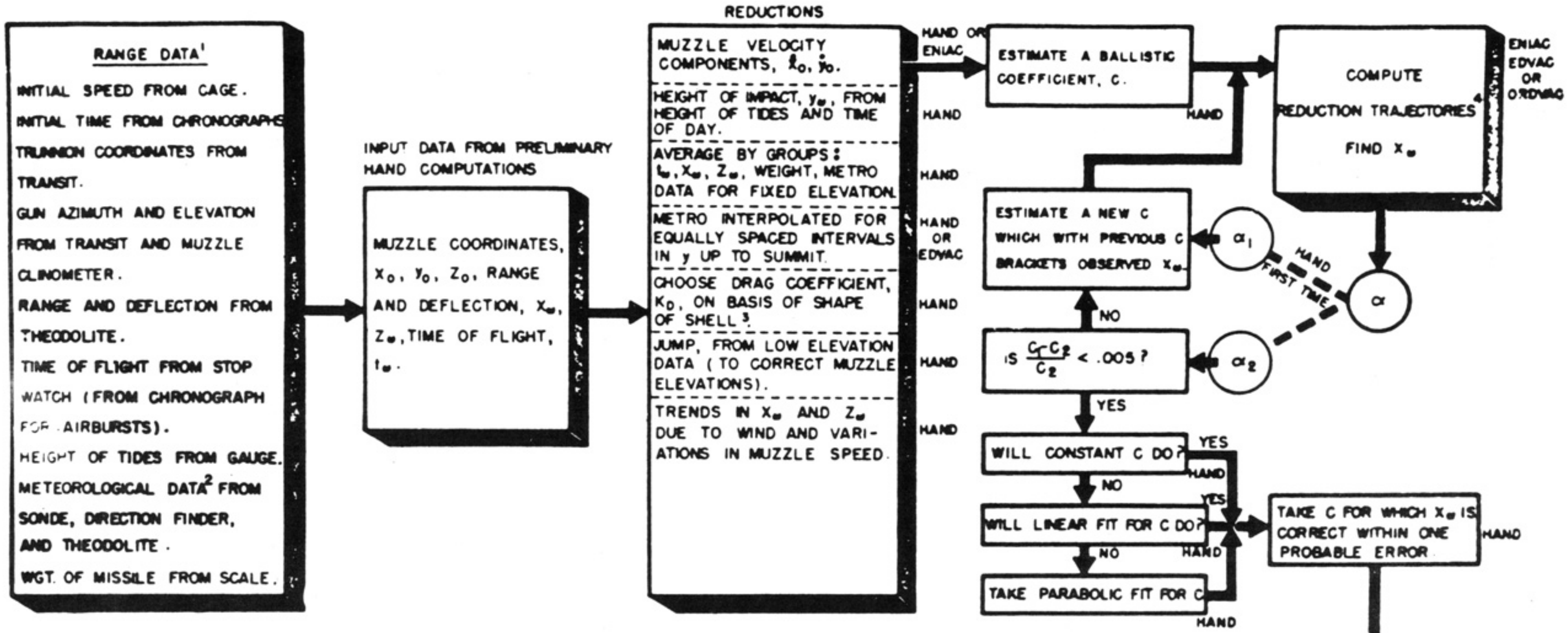
(d) Compute corrections and probable errors.

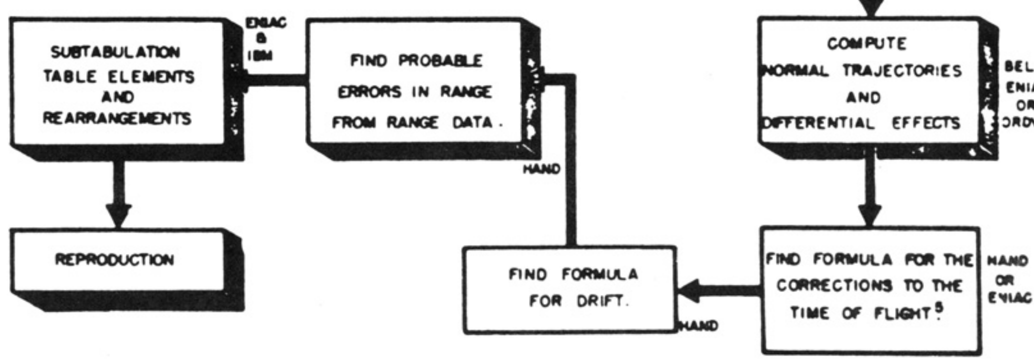
3-8 BALLISTIC COEFFICIENTS FOR BOMBS

The ballistic coefficient of a bomb relates the performance of one bomb to another, particularly in determining whether it will have a high terminal velocity.

For instance, a 500-pound general purpose bomb would have a theoretical limiting velocity of approximately 1000 ft/sec. Actually, because of its shape it encounters extremely turbulent conditions when approaching that velocity or, in fact, when it passes a velocity of 800 ft/sec. To attain this velocity, it must be dropped from an altitude of over 20,000 feet. As an experiment, an antiricochet spike attached to the nose of this bomb enabled it to attain much higher velocities. The spike was approximately 15 inches long and 1½ inches in diameter. This addition to the bomb acted to deflect the shock waves that formed in front of the bomb after it entered the transonic speed zone. The addition of the spike changed the ballistic coefficient of the bomb as well as the form factor.

The ballistic coefficient of a bomb is not selected in the same manner as is that of an artillery projectile. In determining a bomb's trajectory, the range, time of fall, and trail are considered separately for greater accuracy in the final computation. Usually there is a separate ballistic coefficient for range and time of flight; however, these coefficients may be incorporated into a single ballistic coefficient for certain purposes.





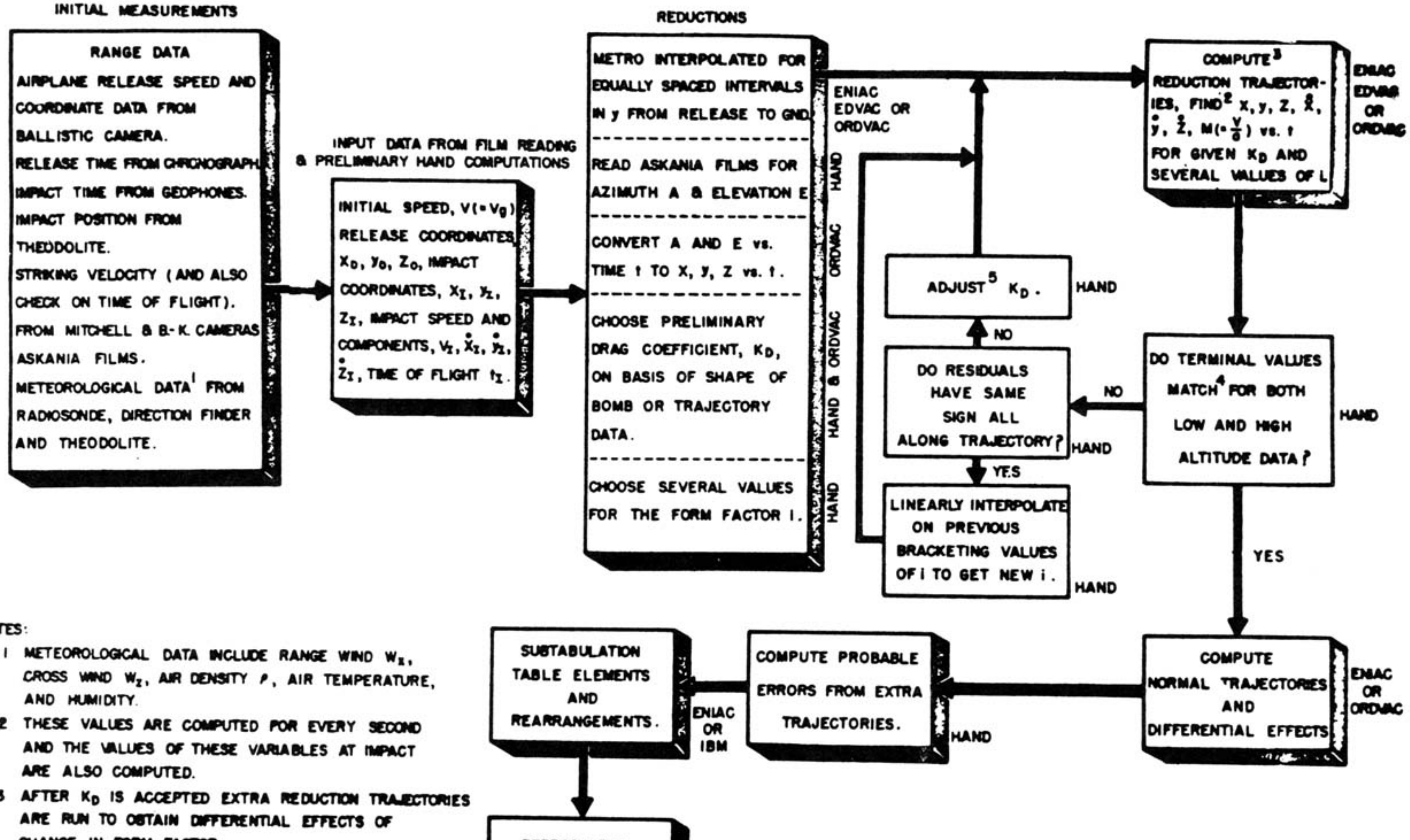
NOTES:

1. DATA GATHERED FOR APPROXIMATELY 10 RD. GROUPS, 5 OR 6 GROUPS PER VELOCITY ZONE, 1 TO 8 ZONES.
2. METEOROLOGICAL DATA INCLUDE RANGE WIND W_x, CROSS WIND W_z, AIR DENSITY ρ, AIR TEMPERATURE, AND HUMIDITY.
3. SOMETIMES A DRAG FUNCTION, $G(v^2/100)$ IS CHOSEN INSTEAD OF CHOOSING A DRAG COEFFICIENT.
4. FINAL REDUCTION TRAJECTORY IS COMPUTED USING LAST COMPUTED C FOR EACH GROUP. LAST FEW REDUCTION TRAJECTORIES YIELD SUCH SPECIAL EFFECTS AS $\frac{\partial X_\omega}{\partial C}$, $\frac{\partial X_\omega}{\partial v_0}$, $\frac{\partial X_\omega}{\partial \phi}$, AND PARTS OF z DUE TO ROTATION OF EARTH AND CROSSWIND.
5. THE t_ω CORRECTION FORMULA IS FOUND BEFORE THE LAST NORMAL TRAJECTORIES ARE COMPUTED.

ADDITIONAL NOTE:

THE BOXES WITH SHADOW CONTAIN SIMILAR OPERATIONS TO THOSE IN BOXES WITH SHADOW IN BOMBING TABLE FLOW CHART.

Fig. 3-11 Flow chart for computation of firing tables.



NOTES:

1 METEOROLOGICAL DATA INCLUDE RANGE WIND W_x, CROSS WIND W_z, AIR DENSITY ρ, AIR TEMPERATURE, AND HUMIDITY.

2 THESE VALUES ARE COMPUTED FOR EVERY SECOND AND THE VALUES OF THESE VARIABLES AT IMPACT ARE ALSO COMPUTED.

3 AFTER K_D IS ACCEPTED EXTRA REDUCTION TRAJECTORIES ARE RUN TO OBTAIN DIFFERENTIAL EFFECTS OF CHANGE IN FORM FACTOR.

4 THE CRITERION FOR MATCH IS THAT THE AVERAGE RESIDUAL FOR ONE GROUP (i.e. SAME RELEASE CONDITIONS) BE LESS THAN THE PROBABLE ERROR OF THE RESIDUALS.

5 THE ADJUSTMENTS ARE MADE FOR HIGH SPEEDS FROM HIGH ALTITUDE DATA AND FOR LOW SPEEDS FROM LOW ALTITUDE DROPS.

ADDITIONAL NOTE: THE BOXES IN SHADOW CONTAIN SIMILAR OPERATIONS TO THOSE IN BOXES WITH SHADOW IN FIRING TABLE FLOW CHART.

Fig. 3-12 Flow chart for computation of bombing tables.

The maximum velocity which any given freely falling body will attain is called the limiting velocity, where retardation due to the air resistance is just sufficient to balance the acceleration due to gravity. Limiting velocity should not be confused with striking velocity. Since the limiting velocity for bombs may exceed maximum speed of any plane, the striking velocity can never exceed the limiting velocity unless some means such as rocket propulsion is used to increase the velocity of the bomb. The following table shows the relation between limiting velocity and the ballistic coefficient.

Limiting Velocity (ft/sec)	Ballistic Coefficient
500	0.33
1000	2.12
1500	9.28
2000	15.88

The value of the ballistic coefficient for the standard 100-lb incendiary bomb is under 1, so that the limiting velocity is only about 600-700 ft/sec. For a heavy armor piercing bomb, a higher ballistic coefficient, 5, is desired.

3-9 TYPICAL BOMBING PROBLEM

When an aircraft, guided on an even forward flight roughly parallel to the surface of the earth, drops a bomb, the following occurs: The bomb will have the same initial forward speed as the aircraft but will have no vertical speed; the bomb will meet resistance from the air and will receive resistance or assistance from the winds, depending on their direction. A typical bombing problem as indicated by Figure 3-13 is established.

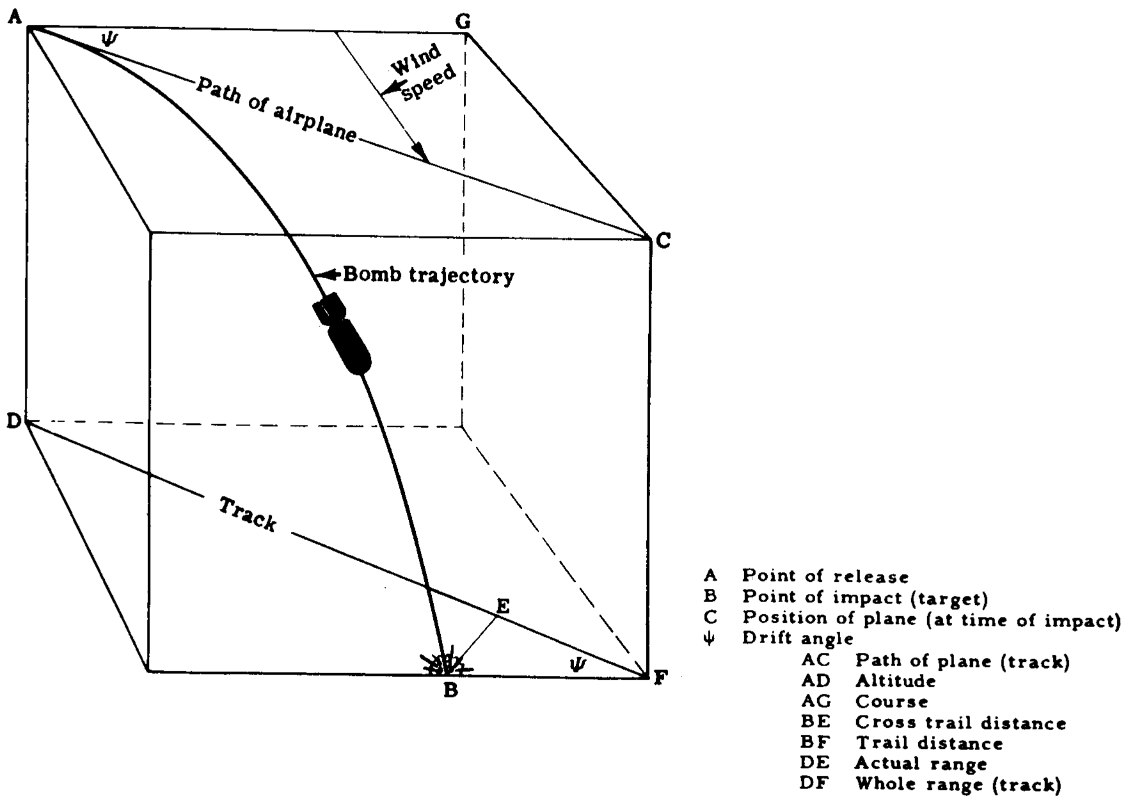


Fig. 3-13 Typical bombing problem.

3-9.1 VERTICAL TRAVEL

Drawn to the earth through gravitational attraction, the bomb falls with an increasing speed. This acceleration due to gravity is retarded by the increasing density of the air as the bomb nears the earth and as velocity increases. The velocity of the bomb increases as it falls earthward, but the acceleration decreases with each second of travel until there is no acceleration and the bomb falls with a constant velocity. This ultimate velocity is known as the terminal velocity of the bomb.

3-9.2 LINEAR TRAVEL

The same resistance forces affect the forward, or linear, movement of the bomb. It meets the resistance caused by the density of the air and may be pushed or retarded by wind forces, depending on their direction of travel. If the bomb could be observed throughout its flight, it would be seen to retain a horizontal position parallel to the airplane for a portion of the flight and then to nose over gradually as it falls away. Due to gravitational acceleration, the angle between the longitudinal axis of the bomb and the axis of the aircraft becomes greater, depending on the time of flight. For present day bombing, it can be stated that this angle never becomes a right angle. As the bomb's downward velocity increases, the resistance forces apply greater pressure and force the axis of the bomb to point more and more toward the earth. As it approaches the earth, the bomb decelerates rapidly on its linear path.

3-9.3 TRAIL

When a bomb strikes the ground or target, it will have lagged a considerable distance behind the aircraft. This distance, known as the trail, is an important factor in the construction of bombsights. The angle made by a line from the aircraft to the point of strike, and a vertical line from the aircraft to the ground is known as the trail angle. Trail is usually expressed in bombing tables as the ratio:

$$\text{trail (mils)} = \frac{\text{trail distance (ft)}}{\text{altitude (thousands of ft)}}$$

For example, given a trail distance of 1000 ft and an altitude of 25,000 ft, the trail is 40 mils.

3-9.4 CROSS TRAIL

As an aircraft moves along its course, it may encounter lateral winds. In order to bring the aircraft over the target, it may be necessary for the aircraft to alter its course to compensate for the effect of the lateral wind. The stronger the lateral wind the greater the cross trail.

3-10 SPECIALIZED BOMBING TECHNIQUES

While the normal bombing problem is associated with the high altitude release of the weapon from a moving aircraft against a stationary target, specialized techniques have been developed to meet particular requirements of both tactical and strategic missions. Included are the skip bombing, torpedo delivery, and circle bombing techniques of World War II. The toss bombing techniques of the Korean War met the requirement for delivery of high explosive and napalm bombs into cave and bunker openings.

An additional requirement placed upon the ballistician has been that of providing safe and accurate low altitude bombing techniques for tactical aircraft armed with nuclear weapons. During an approach "on the deck," the pilot locates a previously selected landmark and releases control of the plane to an automatic system which places the plane in a sharp climb at a predetermined time; releases the bomb; and causes the aircraft to roll over and reverse course. Anticipating a blackout of the pilot, the system remains in control of the aircraft until the pilot takes over (Figure 3-14). Although flight speed over 550 mph (733 ft/sec) is hardly due to low altitude turbulence, the bomb release pattern is analogous to the trajectory of a mortar projectile. Should weather conditions obscure the initial landmark, the pilot may cross the target and immediately go into a sharp climb directly over

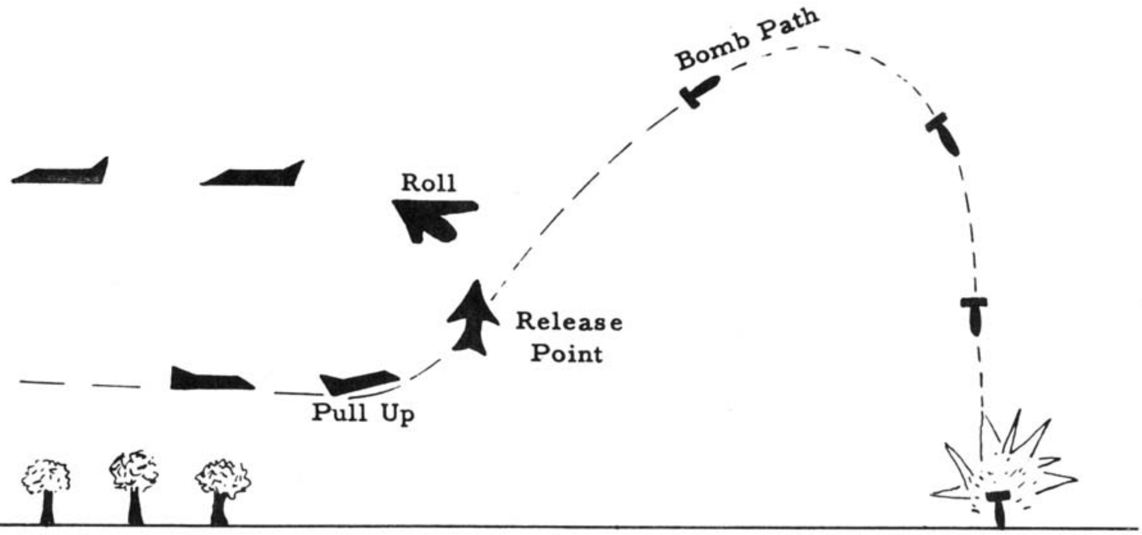


Fig. 3-14 Low altitude bomb delivery.

the target and use an "over the shoulder" release near a point on the climb slightly beyond the vertical. The automatic system is adaptable to this requirement. At the top of the climb the pilot may roll over and reverse his original direction, or because of the loss of flight speed during the climb, dive and change his course to regain flight speed, allowing the plane to leave the target area before the bomb completes its trajectory and detonates.

3-11 STABILIZATION OF PROJECTILES

It is necessary that a projectile travel point first at all times; otherwise, streamlined shapes cannot be utilized in order to reduce air resistance. It the projectile tumbles, loss of range and unpredictable flight will result. Moreover, if the projectile remains pointed in the direction of flight, the design of fuzes and problems of fuze functioning are greatly simplified. Two methods are employed to stabilize projectiles and obtain the desired type of flight; fin stabilization and spin stabilization. Most projectiles are stabilized by a spin imparted by the rifling in the bore of the weapon. The twist of the rifling determines the rate of spin of the projectile and is most important. Projectiles launched by other means may utilize fins to control flight.

3-11.1 FIN STABILIZATION

Since a projectile leaves the bore of a weapon in a nose first position, the fins insure that the base will continue to follow the nose and that the projectile will not veer from its course to any great extent. This is accomplished through an aerodynamic force known as the "crosswind force," which acts on the large surface area of the fins or vanes (Figure 3-15). The crosswind force acts in a direction perpendicular to the direction of motion. It exists because of a difference in air pressure on the sides of the fins and exerts a force against the side on which the pressure is greater. In such a projectile, the fins serve to locate the center of pressure to the rear of the center of mass and thereby establish a restoring moment that causes the projectile to align itself with the direction of motion of its center of gravity.

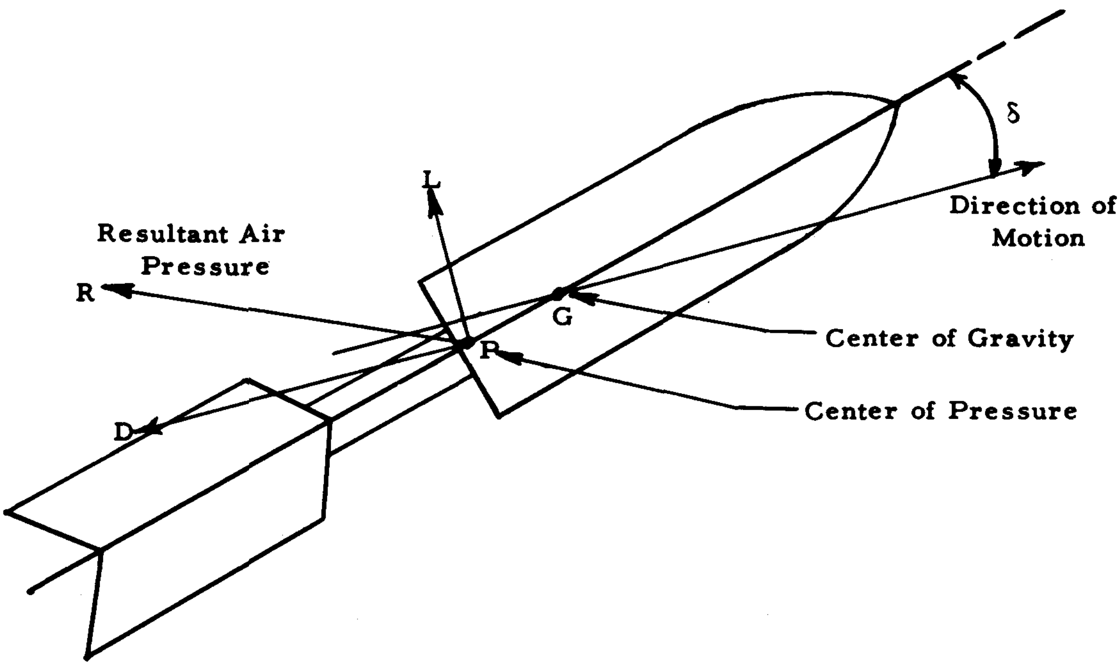


Fig. 3-15 Forces on projectile (CP trails CG).

3-11.2 ROLL STABILIZATION

While it is true that well-designed and well-made finned projectiles will trail properly, asymmetrical fins will exert an additional rudder effect. Thus, a yaw will arise, superimposed on any launching effect, and with it a crosswind force tending to displace the trajectory from that predicted for an accurately made projectile. This phenomenon is of considerable importance in evaluating the hit probability of fin stabilized projectiles and indicates the reason for extremely close tolerances and allowances currently indicated in the manufacture of fins and stabilizers for projectiles, rockets, and missiles.

A practical solution to this problem which appears frequently due to increased numbers of projectiles and missiles employing fin stabilization, is to incorporate into the missile a slow spin (5-15 radians per second) which assists in distributing errors in aerodynamic surfaces over 360° of rotation (angle of orientation, ϕ), thus minimizing errors due to malalignment in production, handling, or launch. The spin rate is cited here to emphasize that roll stabilization does not reach the gyroscopic effects of spin stabilization, nor does it cause the center of pressure to shift forward of the center of gravity. Further, roll stabilization vastly complicates the path and attitude control problems for guidance of missiles (defined in Chapter 5, Part 2).

3-11.3 SPIN STABILIZATION

In a fin stabilized projectile, the center of pressure is located behind the center of gravity. The problem of stabilizing such a projectile is a matter of making certain that the center of pressure follows the center of gravity. In a spin stabilized projectile just the opposite is true. Because of the lack of fins on the projectile, the center of pressure is forward of the center of gravity. The problem of stability in this case is actually one of making center of pressure stay very close to the trajectory which is traced by the center of gravity of the projectile. Any rotating body exhibits certain patterns of behavior by virtue of gyroscopic effects. Possibly the most common exhibition of this effect is a child's toy, a top. When a top is spinning, instead of falling over in response to gravity, it attempts to fall out of the plane containing its own and the vertical axes (Figure 3-16). This attempt to fall rotates

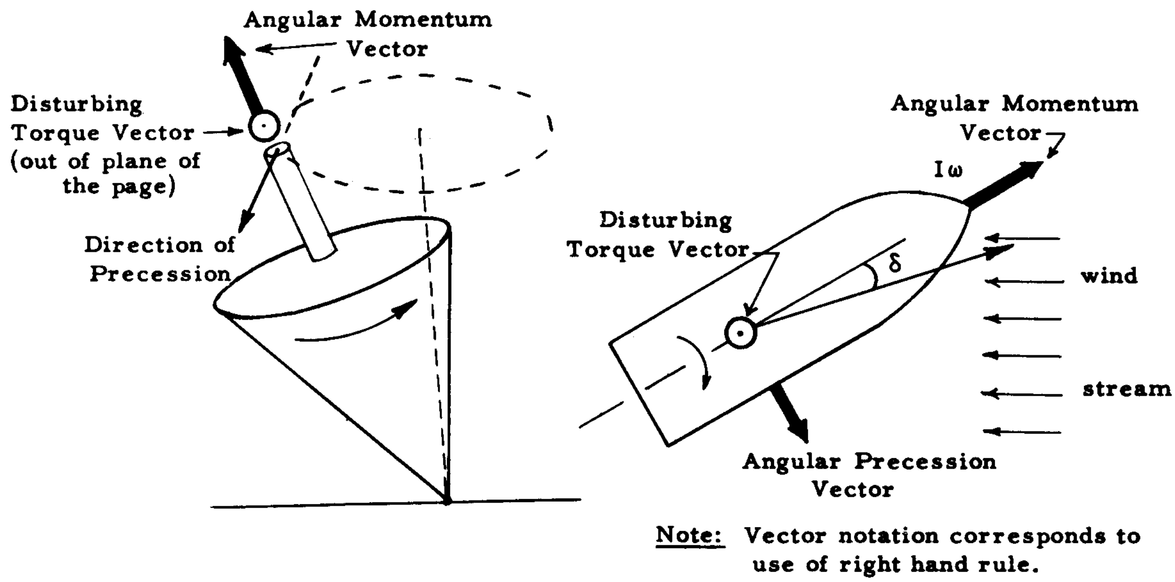


Fig. 3-16 Comparison of spinning top and spinning projectile.

this plane about the vertical. Any point on the axis then describes a circle about the vertical, called precession. The angle that the top may maintain is dependent upon the speed of rotation, and the precession rate is inversely proportional to spin rate.

A spun projectile is stable not only because it is spinning, but also because it is spinning at a rate which results in the maintaining of a small angle of yaw, δ. The rate of spin is determined by the linear velocity of the projectile while in the bore, and the inclination or twist of the rifling. Thus, the rate of spin is a condition which is determined early in the design of a projectile-tube combination.

(a) Overspun projectiles. A spun projectile points constantly in the direction of flight as a result of the gyroscopic effect; the intensity of the gyroscopic effect being dependent upon the the rate of spin; i.e., the faster the rotation, the more stable the projectile. This resulting stability, however, is desirable only when it is below a certain maximum limit for a projectile in flight. If a projectile is too stable, it will fail to nose over on the descending branch of the trajectory. This is because the trajectory drops at a faster rate than the precessing rate of the projectile permits. The result is that the nose, at its lower position, is above the trajectory. It has become so stable and is precessing so slowly that it cannot dip far enough to remain on the rapidly dropping trajectory. As an example, the stability of a small arms bullet causes it to remain pointed in approximately the same direction throughout its trajectory. Thus, it strikes the ground in a more nearly base first position. If a nose-fuzed projectile were overspun, it would not strike the target point first and would probably result in a dud.

(b) Underspun projectiles. As with the spinning top, a projectile will precess slowly when spinning rapidly and will precess more rapidly as its rate of spin is decreased. Finally, if the spin is insufficient, the gyroscopic effect will not be effective and the projectile will be unstable. Before the underspun projectile reaches the descending branch, it precesses rapidly and with large amplitude. Its nose rises far above the trajectory, forming a large angle of yaw. This excessive yaw creates great air resistance, and in addition to causing a decrease in range, the air resistance tends to increase the yaw which eventually develops into a tumble.

(c) Stability factor. The condition for stability of a rotating projectile (Figure 3-17) can be expressed by the factor $\frac{A^2N^2}{4BM}$

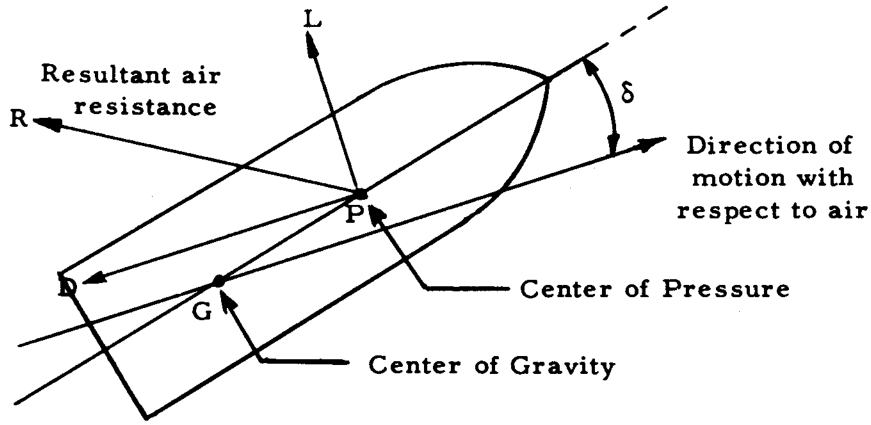


Fig. 3-17 Forces on a projectile (CP leads CG).

where

- A is the axial moment of inertia of the projectile, lb sec^2 ft
- B is the moment of inertia about a transverse axis through the center of gravity, lb sec^2 ft
- N is the rate of spin of the projectile, radians/sec
- M is the overturning moment factor caused by air force R, and is defined as GP $(D + L \cot\delta)$ (ft-lb). Note that the overturning moment is GP $(L \cos\delta + D \sin\delta)$ and is equal to GP $(L \cot\delta + D) \sin\delta$.

The stability factor may be used to predict the degree of stability which a projectile will exhibit in flight. Projectiles having a stability factor less than one will be very unstable, will probably tumble, will lose range, and will produce deviations in accuracy. Projectiles having a stability factor greater than one but less than 2.5 will not tumble, will normally find the nose leading the center of gravity of the projectile throughout the trajectory, and will exhibit a desirable impact attitude for point detonating ammunition. Stability factors greater than 2.5 indicate an overstable round, one which will not track properly since the attitude of the projectile does not deviate throughout the flight (i.e., projectile lands on its base), and is found in small arms and high velocity anti-tank ammunition. In such instances, the high spin rate results in such slow precession that the trajectory is completed before the projectile can effectively nose down on its trajectory.

3-12 STABILITY AND DRIFT FOR SPIN STABILIZED PROJECTILES

Deflection is motion in a direction perpendicular to the plane of fire (Figure 3-5) caused by two major factors: wind effects, which apply to all projectiles and missiles; and, in the case of spin stabilized projectiles, a characteristic deflection called drift. The direction is the same as that imparted by the rifling of the gun tube, right handed for U.S. weapons. The net effect is a gyroscopic precession, inherent to characteristically high spin rates, that not only reflects in the stability factor discussed previously, but the detailed treatment of the mechanism by which a projectile may stabilize itself during the initial phases of flight (considering the disturbing influences of the gun on the projectile presented in Chapter 1, Part 2).

A projectile is launched with an initial angle of yaw which is attributed to the gun itself. As the projectile moves along its trajectory, the curvature of the trajectory becomes greater until shortly after the maximum ordinate is reached. After this, the curvature diminishes again. The effect of the initial curvature of the trajectory is that the air pressure is greatest under the nose of

the projectile since the projectile is pointing slightly above the trajectory. The result in terms of the gyroscopic effect will be to precess to the right. This shift of the axis to the right causes an increase in air pressure on the left side of the projectile nose which, in turn, causes a precession downward. This train of events continues, causing the axis of the projectile to oscillate about a tangent to the trajectory; however, the predominant pointing up of the projectile nose causes an overall right precession. As illustrated by Figure 3-18, in order to meet the stability criteria the initial yaw of the shell must be damped out. For most trajectories with quadrant angles of departure less than 40°, the projectile continues to point to the right except near the gun. (For angles of departure exceeding 65°, drift to the right predominates until the maximum ordinate is reached, following which the drift may be left due to magnus forces predominating; a characteristic of summital yaw.) The summit, likewise, is a critical portion of the trajectory for fin stabilized mortar rounds which are fired at high angles of elevation.

The steady-state solution to the problem of orientation of a right hand spinning projectile about a tangent to its trajectory, is that it flies with a center of motion about its axis to the right of the trajectory (angle ξ) and up (angle η), defined as:

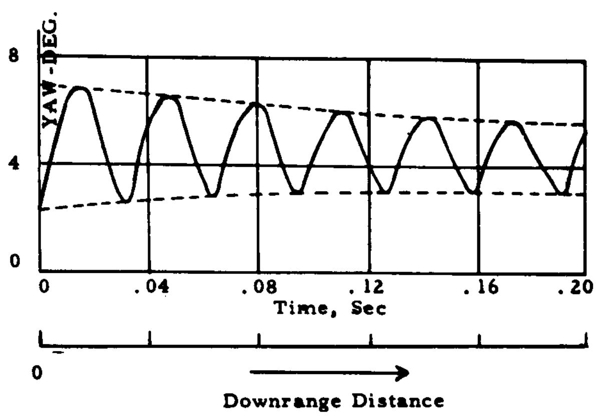


Fig. 3-18 Desirable yaw response-time plot.

$$\xi = \frac{ANg \cos\theta}{\rho\, d^3 u^3 K_m}$$

$$\eta = \frac{-ANg \cos\theta}{\rho\, d^3 u^3 K_m} \left(\frac{K_j}{K_m}\right) \left(\frac{Nd}{u}\right)$$

where

K_j = coefficient of magnus moment and all other symbols are previously defined.

Thus, the general motion consists of epicyclic motion with its center at (ξ, η) instead of tangent to the trajectory, and results in a crossward force in the plane of yaw and a magnus force perpendicular to it.

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2 Hayes, *Elements of Ordnance,* John Wiley and Sons, Inc., N.Y., Chapter X.

3 Kelley, Reno, and McShane, *Exterior Ballistics,* University of Denver Press, Chapters II and IV.

4 *Rocket Fundamentals,* Office of Scientific Research and Development, The George Washington University, 1944, Chapters 4 and 5.

CHAPTER 4

BALLISTIC AND AERODYNAMIC TRAJECTORIES

4-1 INTRODUCTION

The existence of guided missiles which fly ballistic and aerodynamic trajectories dictates specialized treatment of these flight paths. Moreover, interest in long range hypervelocity vehicles has increased with the successful launching of earth satellite vehicles. At this writing the only technically feasible means of returning a man or recovering instruments or films from a satellite orbit is by means of a vehicle decelerated and supported aerodynamically.

This chapter deals briefly with ballistic and aerodynamic (cruise) missiles and with the hypervelocity vehicle which is part airplane and part spaceship.

4-1.1 BALLISTIC MISSILES

A ballistic missile is herein considered as a missile which follows a ballistic trajectory after thrust cut-off. Prior to thrust cut-off, the missile may be directed to a predetermined point in space where its ballistic trajectory begins. It may also be capable of slight path corrections during its terminal fall through the atmosphere. Like the artillery projectile, it has essentially zero lift at the completion of its propulsion phase and from that point is subjected only to the influences of its momentum, gravity, and atmospheric conditions. For short ranges, the ordinate may reach 50 miles; for long ranges, the ordinate may extend to 900 miles above the earth's surface. Ballistic missiles of long range (say 5000 miles) are called "Intercontinental" (ICBM). Intermediate range missiles (say 1500 miles) are called IRBM's. Speeds attained by ballistic missiles (and associated reentry problems) are on the order of Mach 20.

4-1.2 AERODYNAMIC MISSILES

Consideration of trajectories for aerodynamic missiles must reflect the use of wings or airfoils which produce a sizable vertical lift vector. This lift vector is the major contributor in supporting the missile in flight. Aerodynamic type missiles normally fly a flat trajectory which is sometimes referred to as a supported trajectory. Generally, this type of missile uses an air breathing jet engine. Missiles of this category are often referred to as pilotless aircraft and may resemble conventional aircraft in configuration. The early aerodynamic type missiles were restricted to subsonic speeds, but at present, speeds of approximately three times the speed of sound can be attained. The speed and altitude characteristics of aerodynamic paths in general, are shown in Figure 4-1.

4-1.3 HYPERVELOCITY VEHICLES

Hypervelocity vehicles capable of tremendous speeds, have two very attractive features: short time of flight and very long range. A satellite vehicle, for example, can obtain arbitrarily long range over the surface of the earth with a finite speed (about 18,000 mph). The powered flight of a hypervelocity vehicle will probably employ rocket motors. Unpowered flight is characterized by a ballistic, orbital, skip, or glide trajectory.

The principal problem connected with hypervelocity vehicles is the dissipation of heat aerodynamically produced within the atmosphere. To dissipate this heat, specialized techniques are needed, e.g., employment of a coolant fluid.

The ballistic trajectory is found to be the least efficient of the several types mentioned, in that it generally requires the highest velocity at the end of powered flight in order to attain a given range. This disadvantage can be offset by reducing connective heat transfer to the reentry body through increasing pressure drag in relation to friction drag (i.e., using a blunt body). Thus, the kinetic energy required by the vehicle at the end of powered flight may be reduced by minimizing the mass of coolant material which must be carried along.

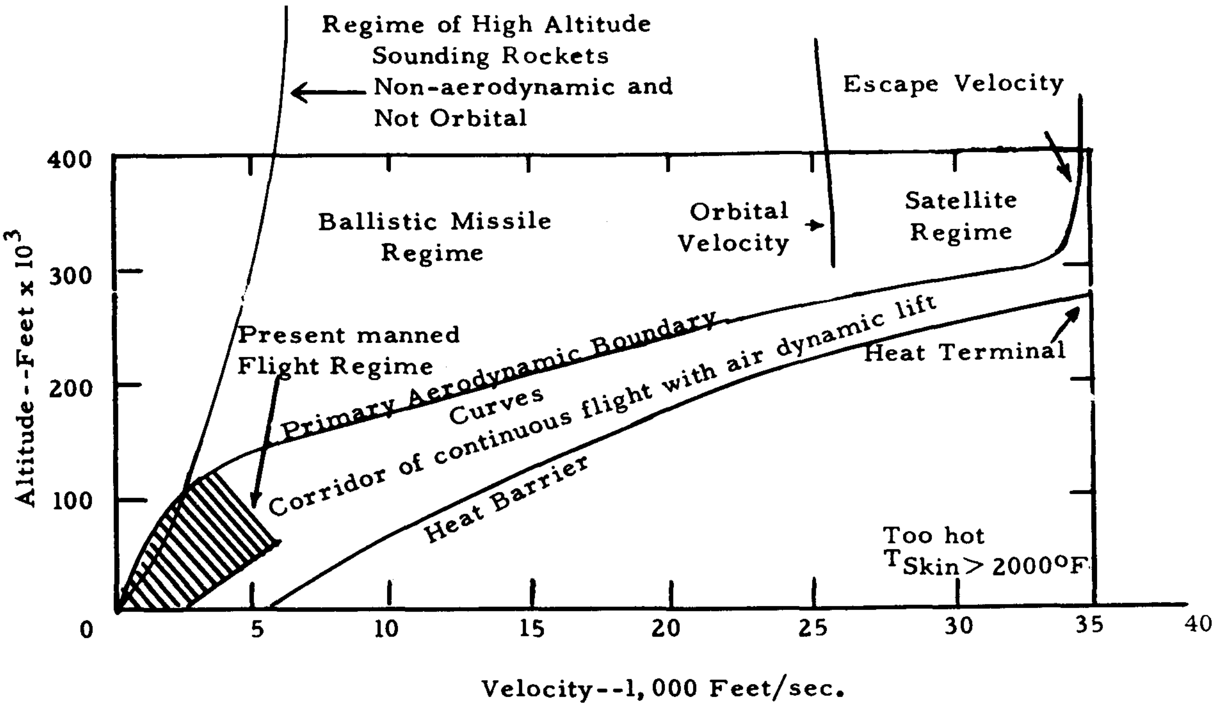

Fig. 4-1 Regimes of atmospheric and extra-atmospheric flight.

The glide vehicle, developing lift-drag ratios in the neighborhood of 4, is far superior to the ballistic vehicle in its ability to convert velocity to range. It has the disadvantage of having more heat connected to it; however, much of this heat can be radiated back to the atmosphere and the mass of coolant material kept relatively low.

The skip vehicle develops lift-draft ratios in the neighborhood of 4 and is comparable to the glide vehicle in its abiltiy to convert velocity into range. Large aerodynamic loads and severe aerodynamic heating are encountered by the skip vehicle during the skipping process; it is therefore concluded that this path is less attractive than glide or ballistic paths for hypervelocity flight.

Delivery systems currently exist (and/or are under development) which utilize these trajectories in accomplishing the system mission of delivering large quantities of high explosive and nuclear warheads. The accuracy and vulnerability of each type of system is a function of all of the variables affecting each trajectory (Figure 4-2).

The decision as to whether a ballistic or aerodynamic (or possible combination) trajectory will be used must precede the preliminary design work on the airframe and will greatly influence the choice of the other elements of the system.

4-2 BALLISTIC MISSILES

During launch and until thrust cut-off, a ballistic missile is supported by the vertical component of thrust from the propulsion system. Following thrust cut-off, it follows a free flight trajectory. Although the concept is simple, the problems confronted in the design of such a missile are tremendous. The forces opposing motion are due primarily to gravity and drag. In such trajectories the variation of the earth's gravitational field at different locations on the earth's

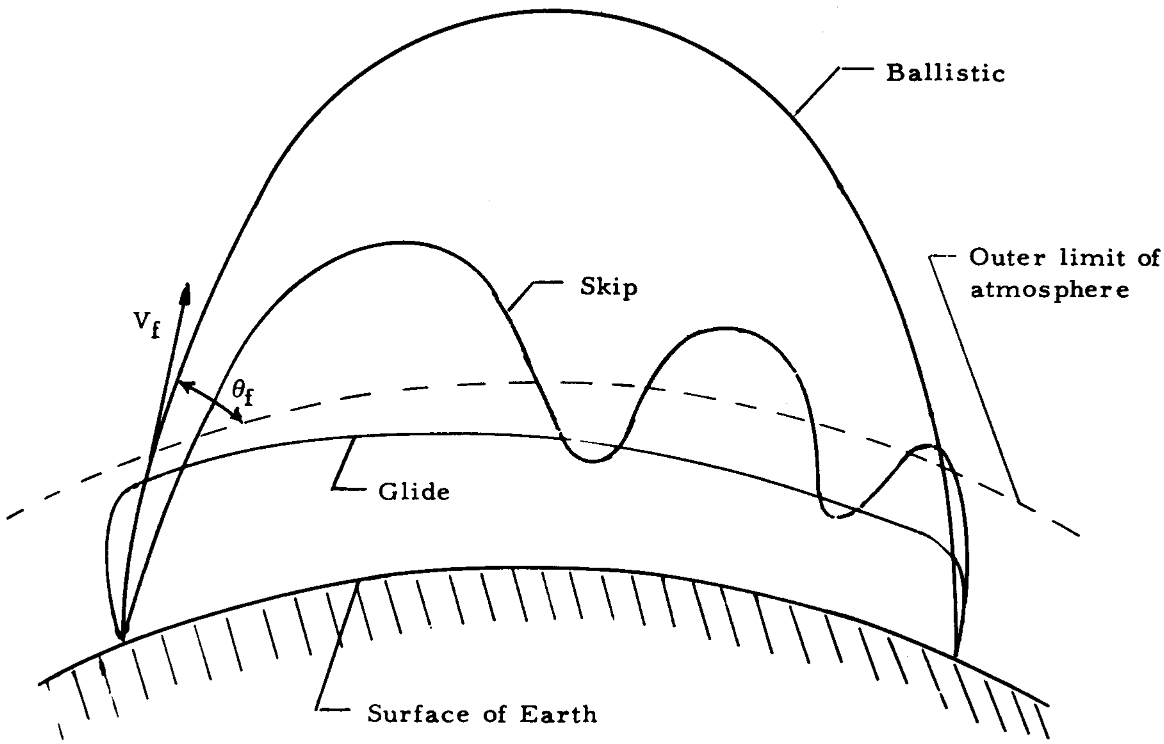

Fig. 4-2 Trajectories for hypervelocity vehicles (vertical scale exaggerated).

surface and at different heights above the earth's surface must be considered (Figures 4-3 and 4-4).

In general, the advantages of a ballistic missile are the difficulty of interception due to tremendous speeds, and the minimizing of time for cumulative error in the guidance system due to short time of flight. Disadvantages inherent in ballistic missiles include tremendous stresses set up in the airframe which require high structural strength; heating problems during reentry phase; minimum response time for the guidance system; and power plant requirements.

It must be noted however, that a missile need not be purely aerodynamic or purely ballistic. Some missiles have a design which incorporates features of both types to varying degrees.

The drag (due to skin friction) which a long range ballistic missile encounters as it re-enters the earth's atmosphere may be excessive at the speeds involved. It is therefore necessary to incorporate into the design a nose cone section which is insulated, dissipates heat, and/or is heat resistant.

4-3 SYSTEMS AND SUBSYSTEMS OF A LONG-RANGE BALLISTIC MISSILE

A ballistic missile may be considered as an assemblage of a number of interconnected and interacting systems and subsystems that perform distinct functions in the accomplishment of the mission of the missile. In a military missile the payload is a warhead (high explosive, atomic, or thermonuclear) that is to be delivered to, and detonated at a predetermined enemy target. The warhead, a subsystem of the missile system, together with its auxiliary equipment (subsystems) such as a fuzing system, is incorporated in the nose cone of the missile.

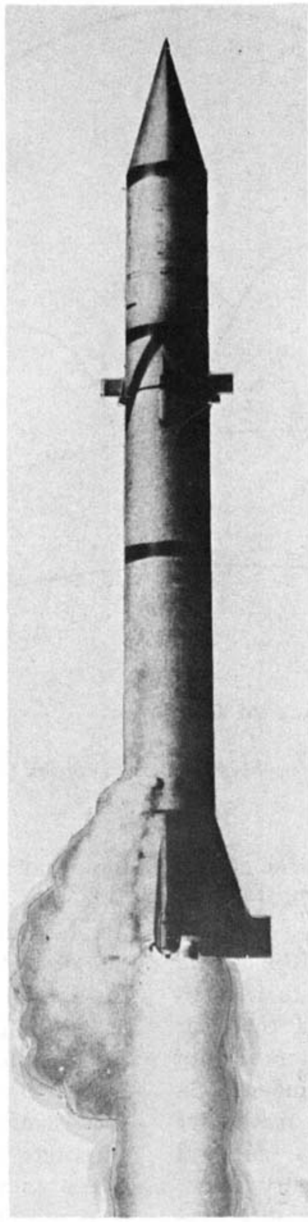

Fig. 4-3 Redstone Ballistic Missile.

Delivery of the warhead to a predetermined target requires inclusion in the missile of a guidance system. This system regulates the position and velocity of the center of mass of the vehicle during powered flight, with the purpose of establishing a satisfactory trajectory prior to thrust cut-off. A control system is also necessary to maintain attitude stability of the missile during powered flight; to prevent undesirable responses when overriding guidance signals are introduced; and to correct deflections caused by winds, gusts, and other disturbances.

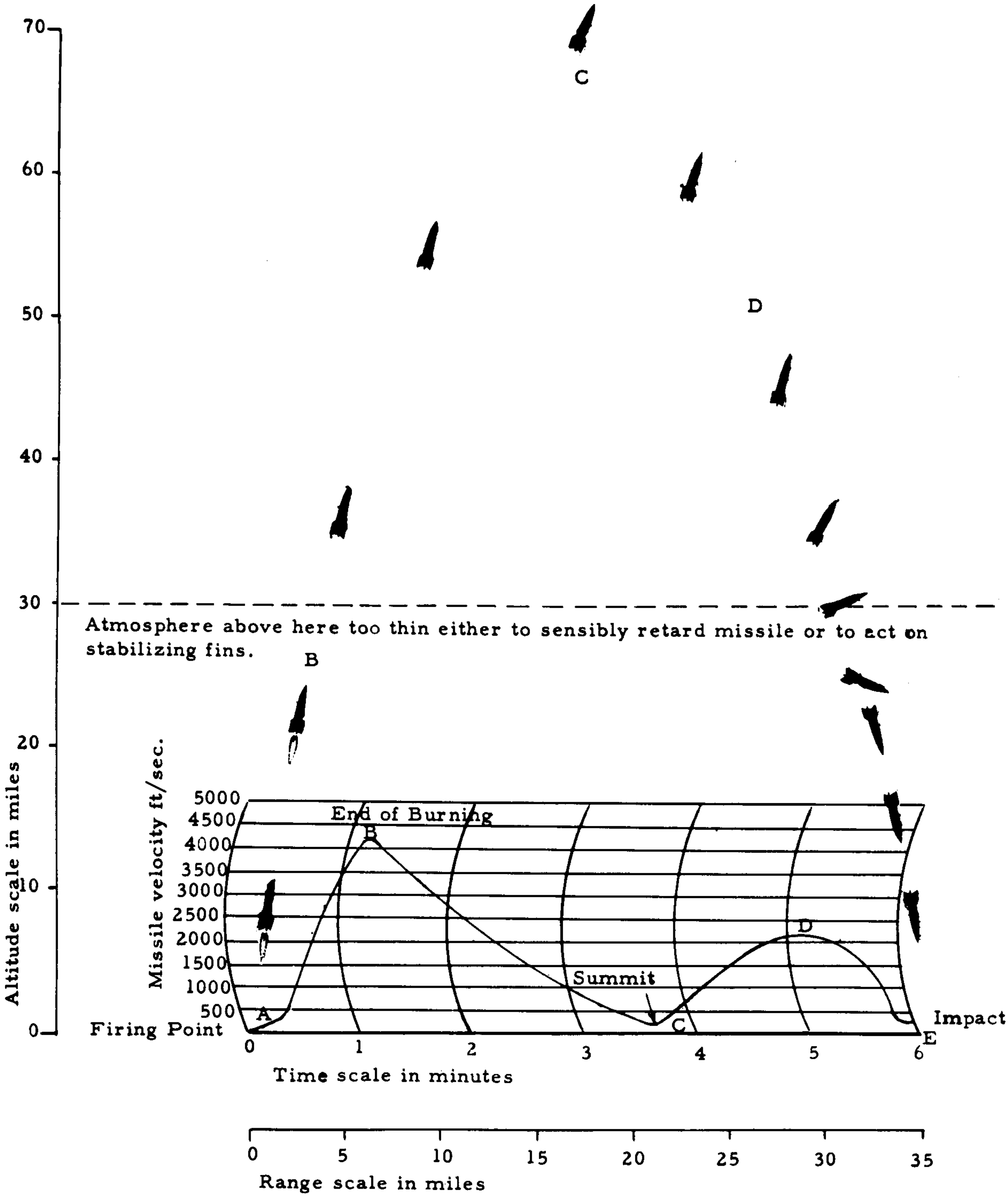

Fig. 4-4 Ballistic missile trajectory (German V-2).

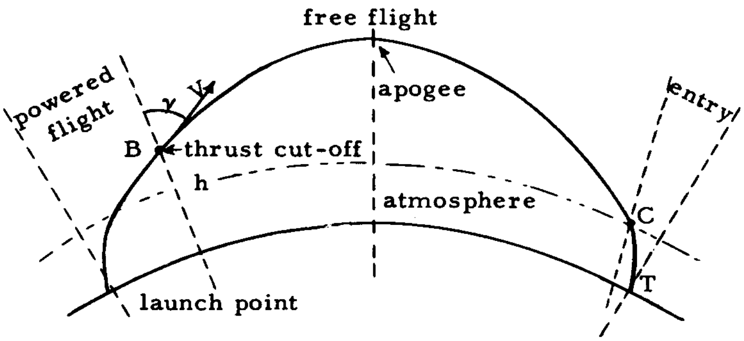

Fig. 4-5 Trajectory of an ICBM.

4-4 POWERED FLIGHT OF THE MISSILE

Power produced by rocket engines is applied to an ICBM or an IRBM only during the initial portion of its flight, from the launch point to the thrust cut-off (point B of Figure 4-5). All major guidance and control of the missile must be accomplished during the powered flight, for the missile motion can be influenced only slightly when power is no longer available.

The ICBM and the IRBM are launched vertically, for this simplifies the launcher required for these large vehicles and also shortens the time that they are within the sensible atmosphere. After this initial vertical climb the vehicle undergoes a programmed turn toward the target. During this turn, the guidance system begins to function and continues to do so until the desired altitude h, speed V, and angle γ are attained (at B, Figure 4-5), whereupon it gives the signal for cut-off of the propulsive power. Perception and correction of vehicle attitude, exercised by the control system, are continuous during the powered flight. Both the attitude of the vehicle and the motion of its center of gravity relative to the required trajectory are adjusted by altering the direction of the thrust of the rocket engines, for instance, by putting jet vanes in the exhaust stream or by gimbaling the rocket thrust chambers.

There are many sets of values of the speed V, angle γ and spatial position of B that will put the nose cone on a trajectory terminating at the desired target; but some sets are more favorable than others in respect to amount of propellant consumed by the engines or required precision of aim. It is the function of powered flight to impart to the nose cone, as accurately as possible, a favorable set of these parameters.

The energy expended in propelling the vehicle during the powered flight increases with the weight of the vehicle. Because both the kinetic and the potential energies are approximately proportional to the weight of the vehicle at thrust cut-off, it is desirable that this weight be as little as possible in excess of the weight of the nose cone. This objective is materially aided by dividing the vehicle into two or more parts, or stages, with each stage containing a rocket propulsion system. Launching is accomplished by starting the engines of the first stage and, in some designs, also of the other stages. At some time during the powered flight the first-stage engines are shut down, and this stage is jettisoned from the remainder of the vehicle. The engines of the next stage are then started, if they are not already operating, and they propel the vehicle on toward B. As the missile nears B, the engines on the last stage are shut down, and the final adjustment of the velocity needed to keep the nose cone on a trajectory that will reach the target is accomplished with rocket engines of comparatively small thrust, called vernier engines. Thus, the term thrust cut-off point (B) refers, accurately speaking, to the point where the vernier engines are shut down rather than to the shutdown point of the engines of the final stage.

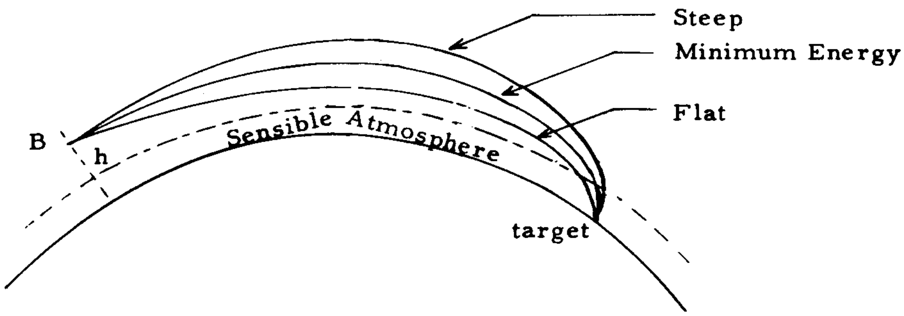

Fig. 4-6 Medium height trajectory.

4-5 EXTERIOR BALLISTICS OF A MISSILE

The trajectory beyond the thrust cut-off point B may be divided into two segments: the free flight portion, from B to the point C of reentry into the atmosphere; the reentry portion from C to the impact point T (Figure 4-5). For a long-range missile, the free flight portion BC is above the sensible atmosphere; hence, the missile during this phase is a freely falling body, the only force acting on it being gravitational attraction. During the reentry portion CT, aerodynamic forces also come into play, and these slow the missile and cause it to become heated.

The length and shape of the free flight trajectory are determined by the speed V of the missile at thrust cut-off; the angle γ between the local vertical at B and the direction of V; the altitude h of B; and the values of acceleration due to gravity g along the trajectory.

Considering a given point B and a given target T, one finds that for every thrust cut-off speed V between the lowest and the highest values needed to reach the target, there are two values of the angle γ that yield trajectories connecting B and T. One of these trajectories is steep; the other is flat. As one decreases the thrust cut-off speed V, these two possible trajectories approach each other, the steeper trajectory becoming flatter, and the flatter trajectory more arched. In the limit, when V attains the minimum value for which the missile will reach the target, the two trajectories merge into a single one of medium height (Figure 4-6). Because this medium trajectory requires the smallest speed V, and therefore minimum kinetic energy at thrust cut-off, it is optimum with respect to propellant requirements. It is also more favorable in other respects. For the steeper trajectory the reentry speed is higher, thus presenting a more formidable heating problem. For the flatter trajectory the reentry path through the atmosphere is longer. Both very steep and very flat trajectories require a more precise guidance system.

4-6 EFFECT OF EARTH'S SPIN AND CURVATURE ON TRAJECTORY LENGTH

A simple picture of a free flight trajectory may be obtained by considering first the case where the range and time of flight are so small that the missile can be assumed to be traveling over a flat and motionless earth, above which the acceleration due to gravity, g, is at every point the same in magnitude and always directed normal to the flat surface (Figure 4-7). For this flat earth situation, the horizontal range from thrust cut-off to impact is given by the expression:

$$\text{Range} = x + \Delta x = \frac{2V^2 \sin\gamma}{g} (\cos\gamma + \sin\gamma \tan\theta) \qquad (4\text{-}1)$$

where Δx is the additional range gained because thrust cut-off occurs at B instead of on the ground at O, and where θ is the angle between the horizontal and the straight line drawn from B to the point of impact.

As the range is increased, the effects of the earth's curvature and rotation become more and

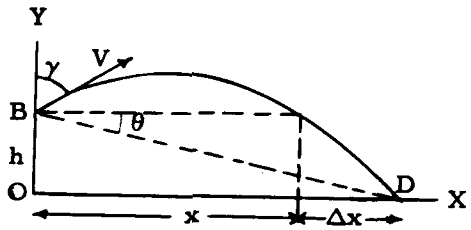

Fig. 4-7 Short range trajectory.

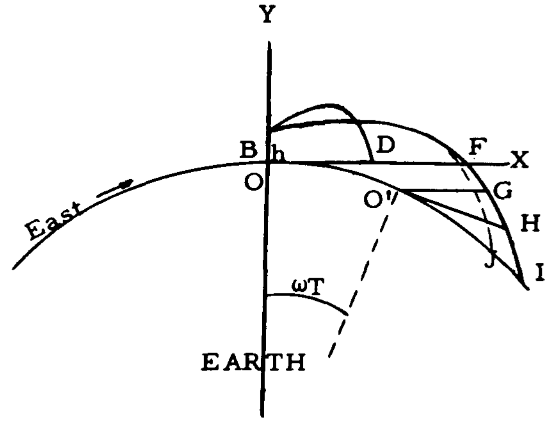

Fig. 4-8 Fixed coordinate trajectory.

more important. A rough picture of how these effects alter the length of the trajectory may be gained by starting with the short-range flat-earth trajectory (Figure 4-7) and adding successive corrections to it. Only the simplest situation will be considered: namely, that of a missile moving in the plane of the equator. Moreover, since the interest here is in a qualitative picture, the mathematical expressions for most of the corrections will not be included. However, it is interesting to note that for as short a range as that of a shot-put by an athlete at the equator, the range for eastward projection turns out to be about an inch greater than for westward projection, all else being equal. For a long-range missile the difference is proportionally still greater.

In Figure 4-8, one should imagine himself as being out in space, off the earth, at some point south of the earth's equator and looking in a northward direction, parallel to the earth's axis. If one could stop the earth from rotating, a missile leaving the thrust cut-off point B would follow the same path as in Figure 4-8, except that OX is now to be regarded as the tangent to the equator at O. This path is changed because the earth actually is rotating and its surface is not flat. In Figure 4-8 the coordinate system XOY is to be thought of as fixed in space, and not as participating in the earth's motions. This means that the origin O does not move and that the missile leaves B at the moment when B is vertically above O.

The trajectory is extended from D to F because the horizontal component of the missile's velocity at B is increased from the locally imparted value $V \sin \gamma$ to $V \sin \gamma + \omega R$, where ω is the earth's angular speed of rotation and R is the earth's radius. The circumferential speed R, which the missile has before launch and retains during flight, is about 1600 ft/sec eastward; this is a sizable correction even for missiles for which $V \sin \gamma$ might be as much as 20,000 ft/sec. Note that for westbound missiles, this effect of the earth's rotation would reduce the length of the trajectory. For motion along any parallel of latitude γ other than the equator, the correction would of course have the smaller value $\omega R \cos \lambda$ eastward.

While the missile is traveling from B to F, the point on the earth's surface directly beneath B has advanced from O *to* O'. This extends the trajectory to the point G because the impact area has been displaced downward, from OF *to* $O'G$, during the missile flight. Such an extension would also occur for a westbound missile.

At O' the apparent horizon is the line $O'H$ which cuts the trajectory at H, and thus the trajectory is extended to H. Notice that this particular extension results from a downward rotation or tilting of the apparent impact area with respect to OX during flight. For a westbound missile the rotation of the impact area, as observed from O', would be upward, resulting in a reduction of trajectory length.

The trajectory is still farther extended, from H to I, because of the curvature of the earth, which gives the missile additional time to acquire range. This extension is positive no matter in what direction the missile is traveling, and would occur even if the earth were not rotating. The longer the range, the greater will be this extension, because the separation of the spherical surface from the plane OX occurs at an increasing rate as the distance from O increases.

The missile would reach point I only if the

gravitational force on it were at every point parallel to the Y-axis. Actually this force is directed toward the center of the earth at every instant of the flight. Consequently a backward component of gravitational force sets in as soon as the missile leaves the thrust cut-off point B, and its magnitude increases steadily with the time since the missile left B. The net effect is to shorten the trajectory so that impact occurs at some point J rather than at I. Actually the backward component of the gravitational force is associated with two different factors. One is the displacement of the missile from the fixed point O as a result of its locally imparted velocity V. This part of the backward component increases with the duration of flight, decreases as the distance of the missile from the center of the earth increases, and would exist even if the earth were not rotating. The other factor is the departure of the missile from O because of its velocity ωR resulting from the earth's rotation. This part of the net backward component is always westward, thus reducing eastward ranges and extending westward ranges.

Although our interest has been mainly to show in a qualitative way how the rotation and curvature of the earth affect the range, it should be said that the method used here can be generalized to cover the case of a missile projected at any latitude and in a trajectory the plane of which is directed in any desired azimuth. For any case, however, the approximations involved in deriving the mathematical expressions for the various independent correction, or perturbation, terms are least objectionable for missiles having small velocities at thrust cut-off.

4-7 THEORY OF BALLISTIC TRAJECTORIES

Although the foregoing approach is useful for illustrative purposes, computations of trajectories of great length must of course be based on Newtonian dynamical and gravitational theory. One starts with the assumption that the earth is a homogeneous sphere and therefore attracts a missile as if all the earth's mass M were concentrated at its center (Figure 4-9). We have then a two-particle problem; that of a missile of relatively small mass m in free flight under the gravitational attraction of another particle, the earth, of exceedingly large mass M. Notice that the only role played here by the earth's surface is to provide launching and impact areas for the missile.

The trajectories to be used in coordinating the preliminary designs of the major subsystems of any particular type of missile are called reference trajectories. For this preliminary phase the trajectories will be sufficiently accurate if computed with respect to a nonrotating spherical earth. Thus, the earth in Figure 4-9 is to be thought of as motionless in an inertial frame of reference: a nonrotating set of coordinates in space that, for all present purposes, may be regarded as having its origin fixed with respect to the center of the sun. Newton's equations of motion then apply in their simplest form, and from them an equation for the various possible free flight trajectories of a missile may be derived. This equation turns out to be the general equation of a conic section. As to whether any particular trajectory will be a parabola or an ellipse, is found to depend on whether the ratio of the missile's kinetic energy to its potential energy at thrust cut-off is equal to unity or is less than unity. Knowing this, one can then show that the speed V of the missile at cut-off determines the type of path as follows:

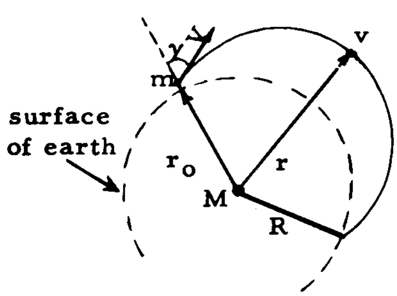

Fig. 4-9 Ballistic trajectory theory.

A parabolic path will result if $V = \sqrt{2GM/(R+h)}$, where G is the Newtonian constant of gravitation; M and R are the mass and the radius of the earth, respectively; and h is the altitude of the thrust cut-off point. Inserting in this expression the known values of G, M, and R, and letting h be, for example, 100 miles, we find that V is approximately 6.9 mi/sec. For this cut-off velocity and any value of the projection angle γ (Figure 4-9), the missile will escape from the earth along a parabolic path.

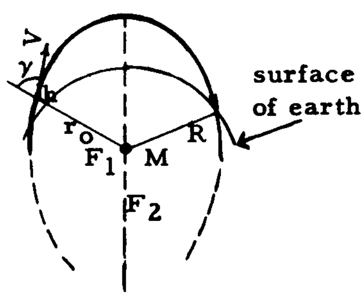

Fig. 4-10 Ballistic trajectory theory.

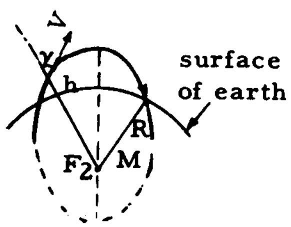

Fig. 4-11 Ballistic trajectory theory.

An elliptical path with its nearer focus at the center of the earth (Figure 4-10) will result if $\sqrt{GM/(R+h)} < V < \sqrt{2GM/(R+h)}$; that is, if V is between about 5 and 7 mi/sec.

A circle surrounding the earth will result if $V = \sqrt{GM/(R+h)}$, about 5 mi/sec, and $\gamma = 90°$. For other values of γ the path will be elliptic, but not circular.

An ellipse with its farther focus at the earth's center (Figure 4-11) will result if $V < \sqrt{GM/(R+h)}$, that is, less than about 5 mi/sec.

It is the last case (Figure 4-11) that is of interest in the ballistic missile program: One can show that to obtain maximum range for any given thrust cut-off speed V, the projection angle γ must exceed 45°. The maximum possible range is half way around the earth, this being obtained when γ is 90° (horizontal projection), regardless of the altitude h of the thrust cut-off point. However, ranges exceeding about four-tenths of the way around become increasingly impractical because of the extreme sensitivity of the range to the angle γ and speed V. To get one-fourth of the way around the earth when h is 100 mi, the optimum values are roughly 70° for γ, 4 mi/sec for V, and 0.5 hr for the flight time.

It is interesting to note the large miss distance which can result from seemingly small errors in velocity at point B. For example, the following data relate miss distances to the casual error at fuel cut-off for a particular ICBM traveling ¼ of a great circle (ground track):

Cause (Error at B)	Effect (Miss Distance)
1 ft/sec tangential velocity	5590 ft
1 ft/sec radial velocity	2310 ft
1 ft elevation	5.85 ft

4-8 SUMMARY OF EARTH SATELLITE VEHICLES

The thrust of a rocket motor has been discussed (Chapter 2, Part 2) in terms of Newton's second law where:

$$\text{Force} = \frac{d}{dt}(mv_e) = \dot{m}v_e + \dot{v}_e m.$$

Total thrust includes a pressure term. If we define an effective jet velocity v_j such that $\frac{d}{dt}(mv_j)$ = pressure thrust + momentum thrust and, further, assume steady state operation of a rocket motor (v_j = constant) it follows that $F = \dot{m}(v_j - V)$ = the force to which a rocket vehicle in "free" space is subjected. This must equal the time rate of change of momentum of the vehicle:

$$-\frac{dm}{dt}(v_j - V) = \frac{dm}{dt}(V) + \frac{dV}{dt}(m)$$

or

$$-dmv_j = mdV \qquad (4\text{-}2)$$

where V, the vehicle velocity, and v_j, the rocket motor's effective gas velocity, are opposite in sense.

For a satellite to maintain a stable circular orbit about the earth, the centrifugal force must

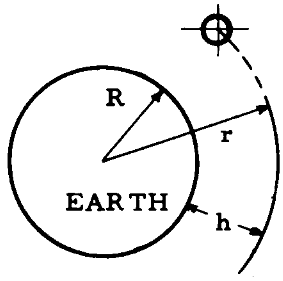

Fig. 4-12 Ballistic trajectory theory.

equal the gravitational force, or $m\ \frac{V_r^2}{r} = g_r m$ where g_r = gravitational constant at radius "r". By the inverse square law, $g_r = g\ \frac{R^2}{r^2}$, where g is the gravitational constant at the surface of the earth; R is the radius of the earth considered as a sphere; and r is the radius of the circular orbit. Hence

$$V_r = \sqrt{\frac{gR^2}{r}}$$

= the velocity required to maintain a circular orbit at height $(r-R)$. (4-3)

Considering the V_r required, the question might arise: "What kind of a single stage rocket can attain V_r?" Solving (4-2) by separation of variables,

$$\int_{V_i}^{V_f} dV = -v_j \int_{m_i}^{m_f} \frac{dm}{m} \tag{4-4}$$

$$V\Big]_{V_i=0}^{V_f} = -v_j \Big[\ln m\Big]_{m_i}^{m_f}, \text{ or}$$

$$\frac{V_f}{v_j} = -\ln \frac{m_f}{m_i} = \ln \frac{m_i}{m_f} = \ln R_m$$

where $\frac{m_i}{m_f}$ is the mass ratio, R_m.

Restating this equation in exponential form:

$$R_m = e^{V_f/v_j} \tag{4-5}$$

$V_f = V_r$ is of the order 18,000 mph for moderate r; v_j for current motors and fuels is of the order 5000 mph. Hence, the mass ratio needed to propel a rocket to orbital velocity (neglecting air drag, gravity, maneuver, etc.) is given by

$$R_m \simeq e^{\frac{18,000}{5000}} = e^{3.6}, \text{ or } R_m \simeq 36.6$$

However, this means that only 2.7% of the original rocket (by weight) would be structure, tanks, motors, guidance, and payload. To date this has been impossible to engineer. But the dilemma can be solved by stacking one rocket on top of another (called staging). Staging essentially requires the integration of (4-4) once for each stage substituting new limits (m_i, m_f, V_i, V_f) for each integration.

In view of the fact that extremely large masses of fuel are required to attain the velocities essential to maintain even a circular orbit around the earth, a space station would be an ideal starting point (or refueling point) for interplanetary space ships. Exploration of the solar system will thus be preceded by the establishment of space "filling-stations" and space ship preparation orbits. Man's knowledge of the nature of the universe will be greatly increased by such explorations.

Of more immediate importance would be the use of a space observatory for astronomical and meteorological purposes. An astronomical observatory outside the earth's atmosphere would have a big advantage over one which has to "look through" the atmosphere. Telescopic definition is greatly impaired by the atmosphere which lacks homogeneity and is in a constant state of minute vibrations. Further, the atmosphere is practically opaque to large portions of the electromagnetic spectrum. A meteorological station which could view the earth as a ball would be able to see storm centers, cloud formations, etc.; in short, the weather situation over nearly half of the globe. Experiments in physics which require nearly complete vacuum could be performed in space: Experiments which demand zero gravity could be performed. FM radio, TV, microwaves, and radar are limited on earth to virtually line-of-sight operation. If three relay stations 120° apart were placed in a 24-hour orbit, their "lines of sight" would blanket the earth and hence, world-wide communications could be effected.

Power for space stations could be supplied by the sun. A large parabolic mirror could focus

the sun's rays on pipes carrying some working fluid (e.g., water). It should be remembered that a heat engine operates best when the low temperature part of the system (sink) is at a very low temperature. On the shadow side of a space station, temperatures approach absolute zero.

The effects of zero gravity on chemical reactions and physical and biological processes are not, at present, known. Perhaps studies in space would result in discoveries of extreme importance.

The military value of a space station could be decisive. Imagine the advantage of having a world-wide and instantaneously accurate situation map! Imagine being able to see a missile at all times from launch to target! Imagine knowing what type of work an industrial complex is doing! The military importance of space stations is tremendous.

4-9 AERODYNAMIC MISSILE CONFIGURATION

The design of an aerodynamic missile is based on design criteria for subsonic and supersonic aircraft which makes the aerodynamic missile virtually a pilotless bomber. For subsonic speeds, fluid flow theory has been developed to the point where very accurate calculation of the lift and drag forces and moments acting on an aerodynamic body is possible, as long as the Mach number is less than about 0.8. The same is true, although to less extent, at supersonic speeds as long as the Mach number is greater than about 1.2. In the transonic range between 0.8 and 1.2, the approximations made in both subsonic and supersonic theory are not valid, so that design work is complicated, because calculation must be based entirely upon experimental data (Figure 4-13). Moreover, the transonic region is a critical one in which there is a sharp rise in the drag coefficient and a sharp drop in the lift coefficient of such magnitude that the label "sonic barrier" has been attached to it. Fortunately, this region does not constitute an impenetrable barrier. By using powerful jets and rockets of skillfully designed configurations, the barrier has been reduced simply to a region of inefficient operation. It should not be concluded that the design problem has been solved completely. Exhaustive research is continually supplying new information to form the basis for the design of new and better configurations for aerodynamic missiles.

The final missile body design involves a compromise of many conflicting requirements, and at supersonic speeds this becomes an extremely involved problem. For example, reduction of drag for a supersonic missile would generally indicate a slender missile body with very thin airfoils. These requirements are not wholly compatible with the requirements of stowage space for components, such as guidance and control equipment, and with structural strength. Hence, compromises must be made to arrive at an optimum design.

In the design of an aerodynamic configuration, the wing design to support large heavy bodies at sustained great speed requires new techniques. The problem is somewhat different from normal aircraft design in which takeoff and landing requirements are important features. The relatively high longitudinal acceleration encountered by some surface-to-air and air-to-air missiles during and immediately following launching, requires that these missiles have great structural strength along their longitudinal axes. Certain missiles are called upon to execute turning maneuvers which impose great lateral accelerations on the missile's structure. At present, sonic missiles are being designed to withstand a maximum acceleration of approximately 60 g's longitudinally, and 20 g's laterally. Accelerations of this magnitude create stresses on the structural members of the missiles far greater than the stresses encountered in conventional aircraft structures. For example, today's jet fighter aircraft (such as the F86 Sabrejet) are designed to withstand a maximum acceleration of approximately 12 g's.

Concerning supersonic speed through the atmosphere, the problem of heat transfer and heat resistant materials is far greater than is generally realized. It has been pointed out by leading

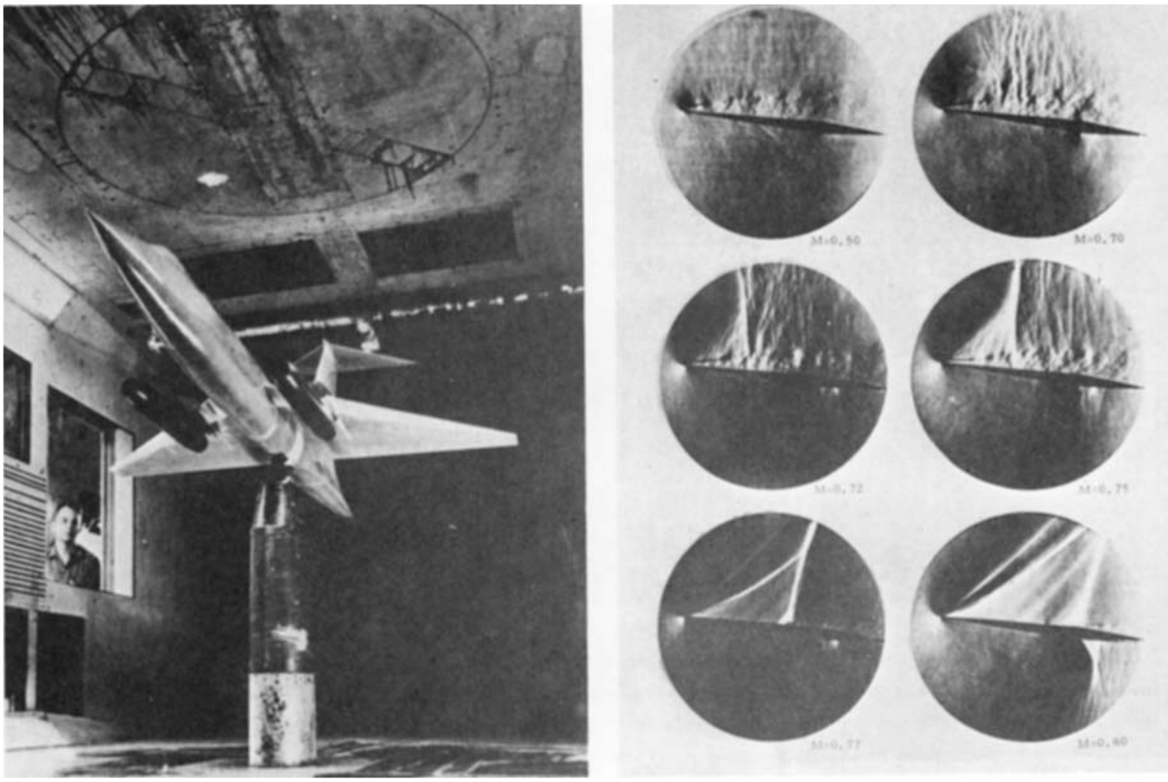

Fig. 4-13 Jet-age aeronautical scientists must assure stability in aircraft over a wide range of speed. Using a high speed research model built for special studies in the 300-mph, 7x10-foot wind tunnel at NACA's Langley Aeronautical Laboratory, scientists evaluate stability characteristics in subsonic flight (e.g., during landing and takeoff) of an aircraft capable of supersonic flight. Automatic recording devices in the adjacent control room measure forces exerted on the test model. The series of spot photographs show the effect of increasing speeds on the shock wave patterns over a supersonic airfoil.

scientists that there is virtually no limit to attainable speeds except as limited by the heating effect of atmospheric friction. At high temperatures most materials now available lose their structural strength. As an example, one ballistic type missile experienced skin temperatures of over 900°F, and it was necessary for the designers to insulate the inner side of the skin with several inches of fiberglas in order to protect the fuel tanks and certain other missile components (Figure 4-15). Even so, much trouble was experienced when in some cases heat due to air friction caused "cooking off" (premature explosion) of the warhead.

In designing the configuration of supersonic aerodynamic missiles many theoretical calculations and much wind tunnel data must be accumulated in determining the airfoil design and the design of the plan form of the aerodynamic surface.

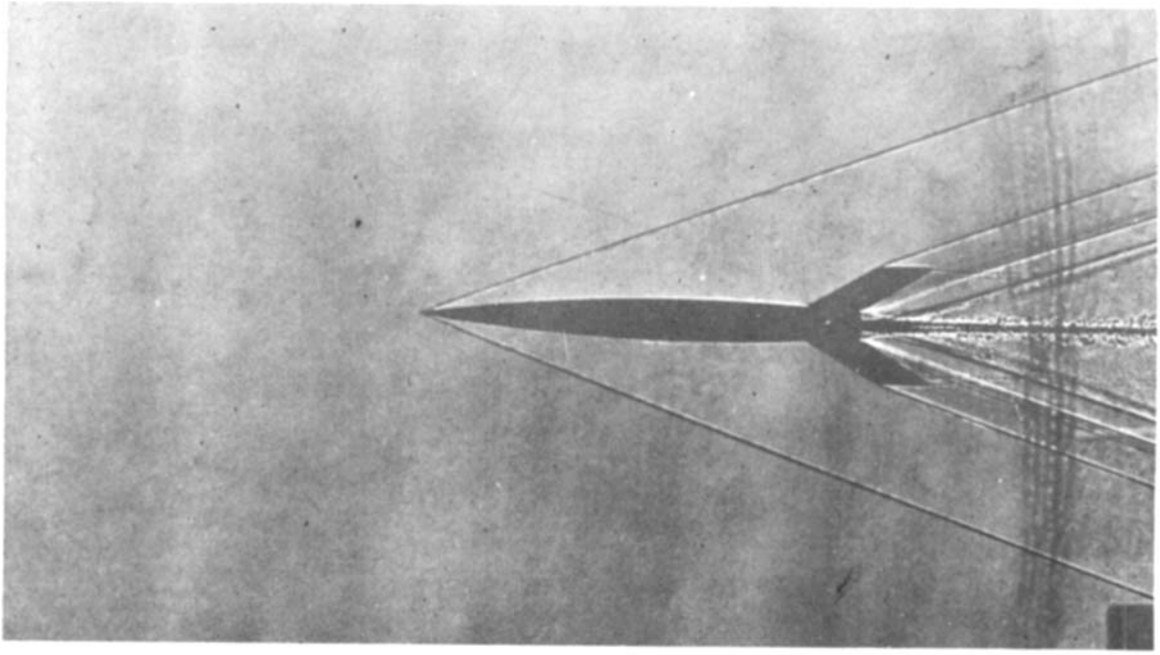

Fig. 4-14 A missile model "streaks along" at more than 2000 mph in an NACA supersonic free flight wind tunnel at the Ames Aeronautical Laboratory, Moffett Field, California. This vivid shadowgraph shows shock lines streaming back from the model's needle nose and tail surfaces. During sustained flights at such high speeds, aerodynamic heating could raise the missile's surface temperature to more than 600°F.

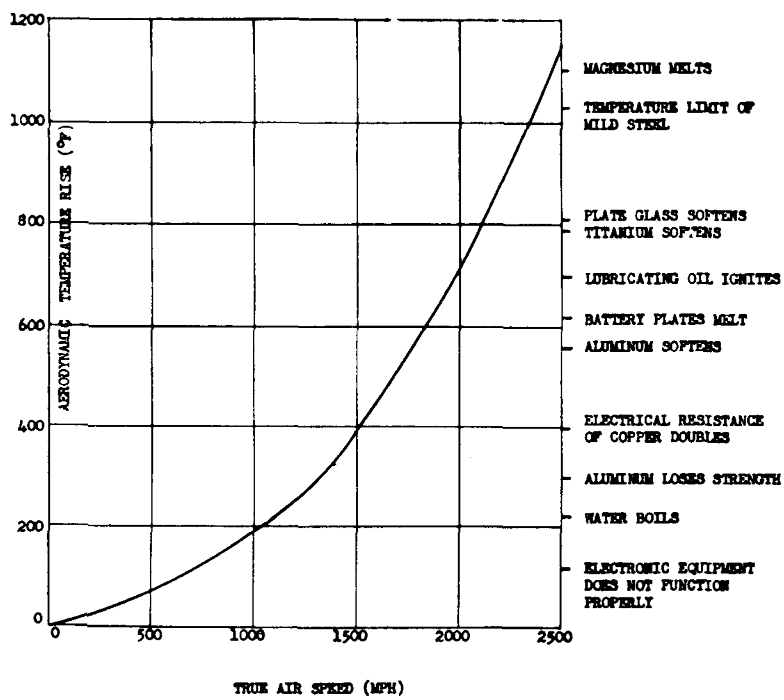

Fig. 4-15 Heating effect of atmospheric friction.

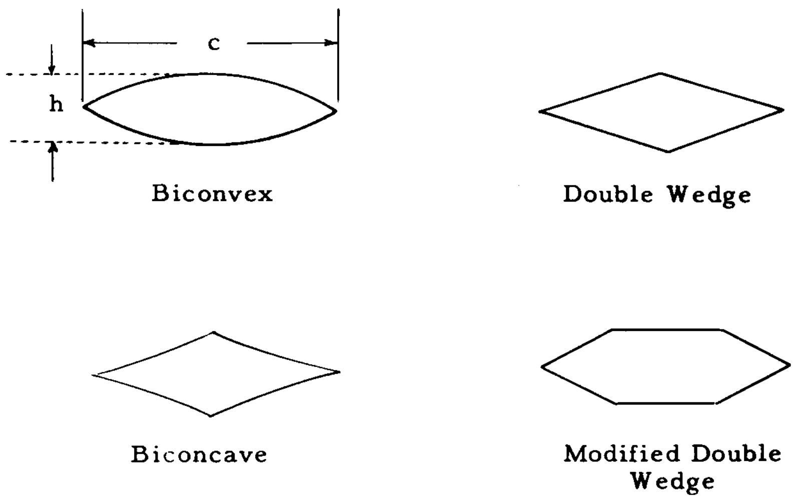

Fig. 4-16 Double symmetric supersonic airfoils.

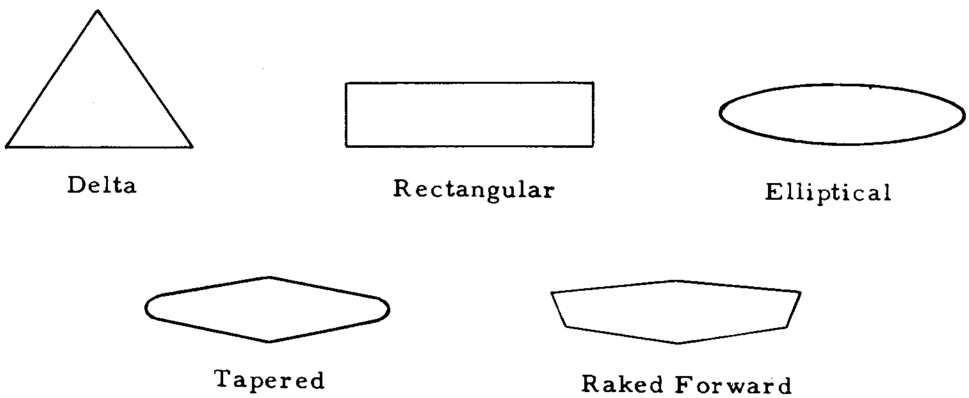

Fig. 4-17 Supersonic aerodynamic surface plan forms.

4-9.1 PROFILE SHAPES

The thickness ratio is often used to describe an air foil. It is defined as the ratio of the maximum thickness to the chord length, h/c. It is generally about 4% for supersonic airfoils. Profile shapes are divided into two main classes: double symmetric, that is, symmetrical about the chord and perpendicular to the chord at its midpoint; and asymmetric, that is, unsymmetrical about the chord line or unsymmetrical about the perpendicular chord line at its midpoint. However, in general, supersonic profiles are symmetrical about the chord. Several different geometric configurations of the double symmetric type are shown in Figure 4-16. The most popular of these airfoils is the modified double wedge, which has the best strength properties and is relatively easy to manufacture.

4-9.2 PLAN FORMS

Several plan forms for supersonic wings are shown in Figure 4-17. For the tapered plan form, the leading edge may be tapered, or both leading and trailing edges may be tapered; in addition, the taper may not be the same on each edge. The wing tips for any of the plan forms may be squared, rounded, or raked forward or aft. Some current experiments on odd wing shapes are being conducted to reduce the aspect ratio, *AR*. There is also research being conducted on canard configurations which utilize forward control surfaces while the rear fins produce the lift; and research on blunt trailing edges for stability and control at transonic speeds. Various aerodynamic steering methods are shown in Figure 4-18.

At transonic speeds it is desirable to utilize

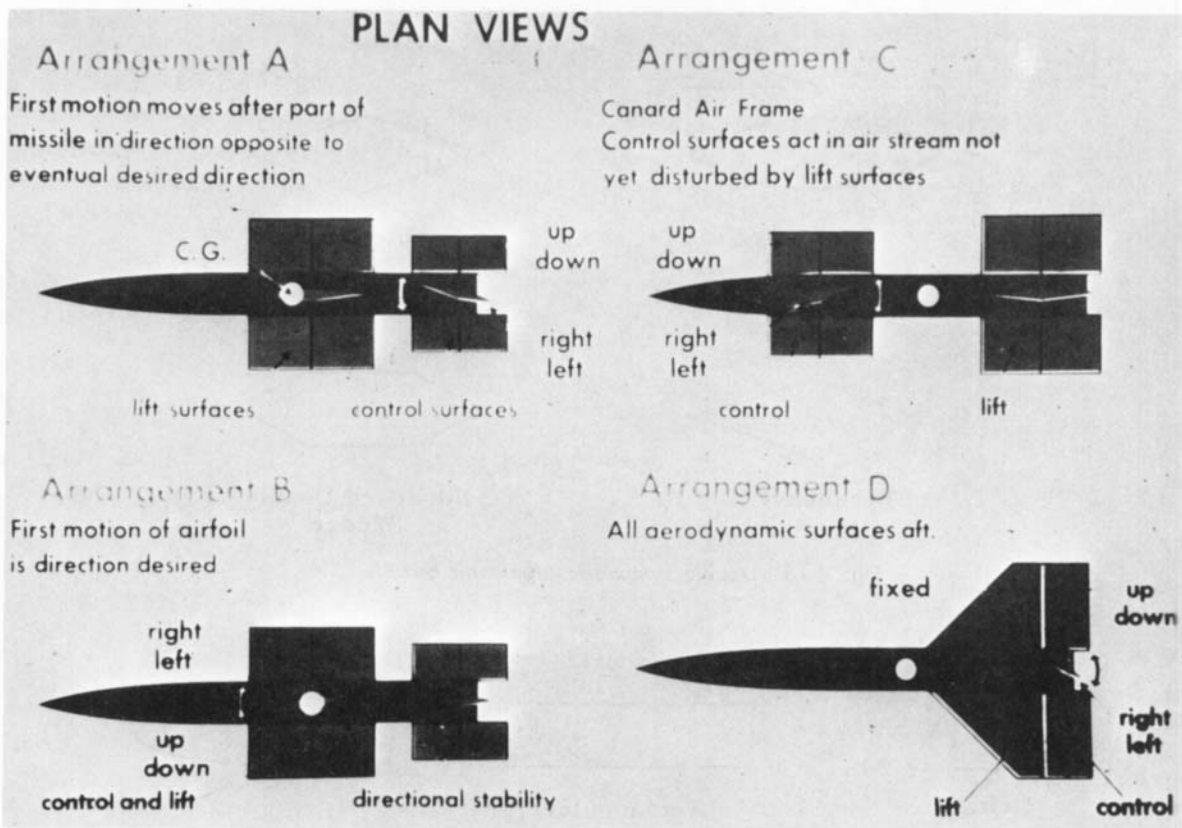

Fig. 4-18 Aerodynamic steering methods.

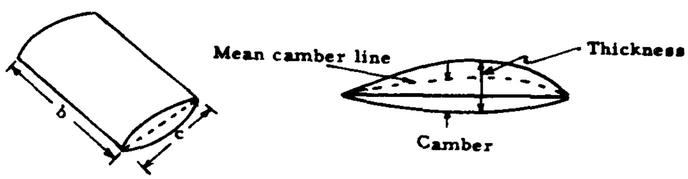

Fig. 4-19 Nomenclature for airfoil configuration.

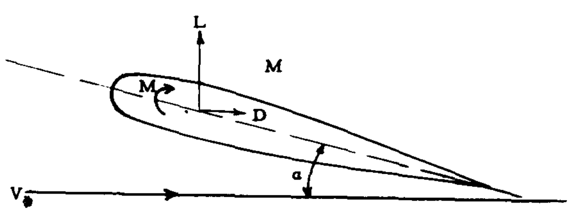

Fig. 4-20 Forces acting on airfoil at angle of attack, α.

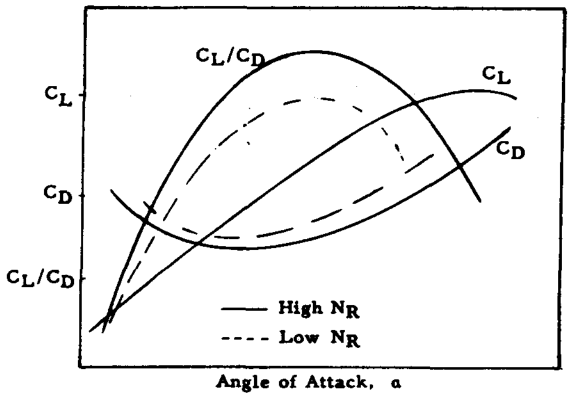

Fig. 4-21 Variation of lift and drag coefficient with angle of attack for typical airfoil.

swept-back wings, because, in this speed range, the compressibility of air must come into consideration and a swept back wing will forestall a sharp increase in wing drag due to compressibility of the air and the ensuing formation of a shock wave. However, at supersonic speeds this wing configuration produces undesirable wind-body interference and torsional bending, resulting in center of pressure shifts. That is why many supersonic missiles have a straight wing plan form. A swept back wing is generally less stable and provides less lift than a rectangular wing. This is due to a decrease in the aspect ratio, *AR*, and greater body interference, since more of the wing surface is closer to the body.

In wing design, the main objective is to secure maximum lift and minimum drag consistent with structural and stability requirements. An actual wing may be complicated by such considerations as taper, sweepback, twist, change of profile, and control surfaces. Basic data are usually developed in terms of a simpler structure, the airfoil. In Figure 4-19, an airfoil has been sketched to illustrate span, *b*, chord, *c*, camber, and thickness. Area, S, is defined as the product, *bc*, and aspect ratio (AR) is defined as $b^2/S = \frac{b^2}{bc} = \frac{b}{c}$.

An airfoil moving with respect to the atmosphere is subjected to the lift (L) and drag (D) forces (Figure 4-20). The angle of attack α, lies between the direction of the relative wind and the chord line. Moment (M) acts as indicated.

The expressions for these basic parameters are developed below and are similar to the expressions for cross wind force and drag developed in Chapter 3), d^2 being proportional to the area S (Figure 4-20).

$$L = \frac{1}{2}\rho V^2 S C_L$$

$$D = \frac{1}{2}\rho V^2 S C_D$$

$$M = \frac{1}{2}\rho V^2 S c C_M$$

The coefficients depend on angle of attack, aspect ratio, profile form, and to a degree on Reynold's number (Figure 4-21). The general characteristics are illustrated for an aspect ratio of 6.

The early version of the F-102 interceptor was a sharp disappointment: it would not break through the sonic barrier. Salvation came in the form of the "Whitcomb area rule," a revolutionary method of tailoring aircraft wings and fuselage to minimize interference drag in the critical transonic speed range. Aircraft flying at low speeds push air ahead of them, but the resistance of the air thus compressed is negligible. As the aircraft approaches the speed of sound, the air compressed by its passage forms a shock wave that is forced back along the body. The pinched waist of the area-rule fuselage gives the compressed shock wave a chance to expand; this reduces the drag on the aircraft. The resulting large improvement in aerodynamic efficiency allows an aircraft like the F-102 or the B-58 to "slip" through the sonic barrier instead of needing considerably more thrust in order to "burst" through. It is regarded by the NACA, the armed services, and the aircraft industry as a major key to supersonic flight (Figure 4-22).

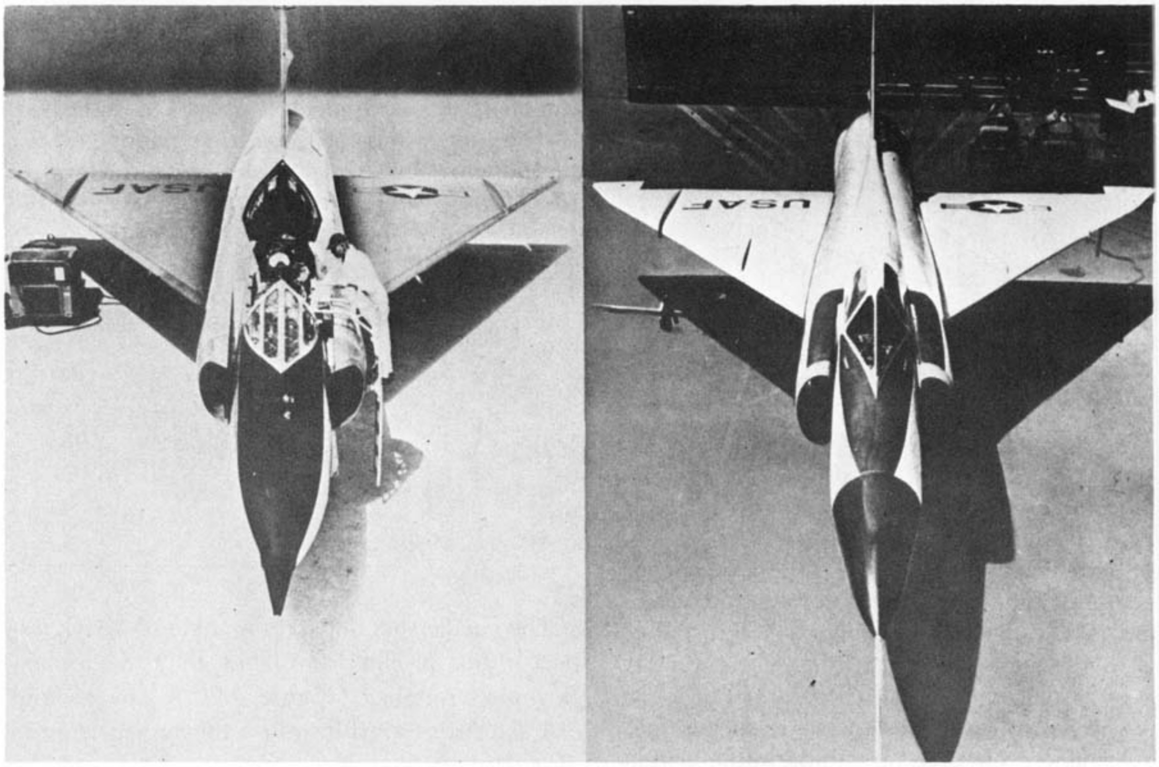

Fig. 4-22 Illustration of Whitcomb area rule.

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CHAPTER 5

GUIDANCE FOR CONTROLLED TRAJECTORIES

5-1 GENERAL

When a projectile is fired from a gun at a target, it is launched in such a way that the predicted external forces acting upon it during its flight, will direct it toward the target. The target will be hit if the user has sufficient skill in choosing the correct trajectory based upon the ballistic characteristics of the projectile, the current meteorological conditions, and target motion. The firer can control only the launching conditions. It is completely impossible to make corrections after launch, therefore any change in target vector or meteorological conditions during flight will result in a miss; further, any error in the launch phase will also result in a miss.

The advantages of being able to control the flight of a missile after the launch stage are numerous: Launching errors are now of less importance because they can be corrected. The behavior of the target need not cause a miss because the missile can correct its course for up-to-date target information. A missile that can be controlled during its flight requires a guidance system, or perhaps several different systems, i.e., a separate system for initial, midcourse, and terminal guidance. A guided missile guidance system accomplishes the two forms of control shown in Figure 5-1. Both attitude control and path control are necessary to achieve accuracy. This complete system will then allow the path of the missile to be adjusted after launch along a trajectory which will lead it to the target.

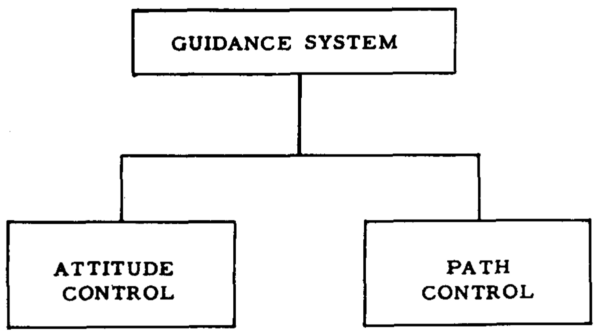


Fig. 5-1 Guidance systems.

5-2 ATTITUDE CONTROL

Attitude control is the angular orientation of the missile about its center of gravity and can be divided into three functions: yaw, pitch, and roll (Figure 5-2).

(a) Yaw is the angular motion of the missile about an axis which is perpendicular to the longitudinal axis of the missile, and lies in the vertical plane passing through the missile center of gravity.

(b) Pitch is the angular motion of the missile about an axis which is perpendicular to the longitudinal axis of the missile, and lies in the horizontal plane passing through the missile center of gravity.

(c) Roll is the angular motion of the missile about it longitudinal axis.

The necessity for maintaining attitude control can be explained as follows. First, the missile must proceed along the flight path keeping drag force to a minimum. Any unorthodox attitude of flight can be corrected by moving the missile in yaw, pitch, and roll. Next, the missile has to have a certain amount of built-in intelligence. It must know up, down, right, and left. Considering the result of a 180° roll error of the missile, the down fin is now on top and the positions of the left fin and the right fin are reversed. A command to the missile to go left actually causes the missile to go right. This shows vividly that attitude control must be achieved before commands for path control will effectively guide the missile to the target.

Missile guidance components required to provide attitude control normally include the following:

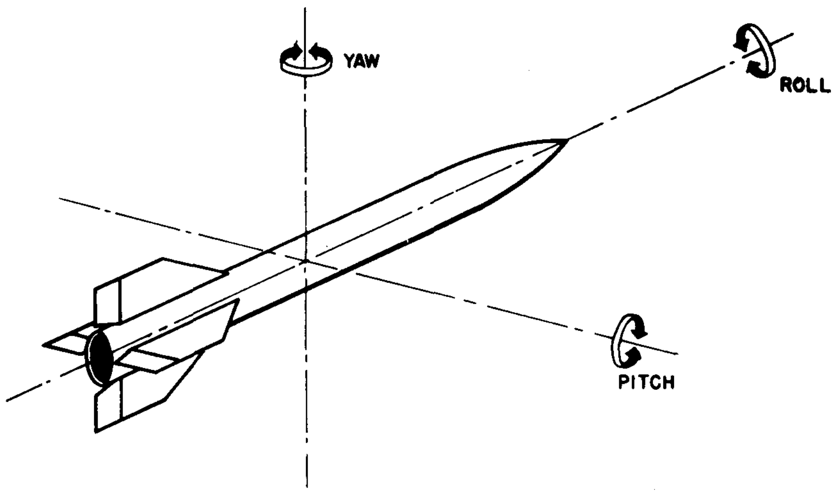


Fig. 5-2 Yaw, pitch, and roll axes.

(a) Gyros, to provide reference directions along the principal axis of spin for yaw, pitch, and roll motions. Normally, when properly mounted, two gyros will suffice to provide reference to these three axes of motion.

(b) Differential, to detect errors between alignment of gimbal axis of gyros and axis of missile airframe to provide a signal in both magnitude and sense.

(c) Computer, to compare error signals with a programmed or command flight path and prepare signals, which when amplified and applied to control system will cause the missile to respond properly.

(d) Controller, to amplify the small signals from the computer and energize the control system.

(e) Effectors, to regulate missile response in terms of computer solutions by means of moving aerodynamic surfaces, jet vanes, gimballed motors, or activating auxiliary jets.

5-3 PATH CONTROL

Most guidance systems are named according to the type of path control which they have. Path control is the control of the missile's linear displacements in the lateral, normal, and range directions, referenced to an ideal flight path.

(a) The lateral direction is, generally speaking, either to the left or to the right of the correct trajectory. Specifically, it is used to describe motion of the missile on a horizontal line which is perpendicular to the trajectory. When a lateral error exists, a yaw of the missile is needed to bring it back to the path. Therefore, yaw attitude control and lateral path control are associated.

(b) The normal direction is used to describe motion of the missile along a line which is perpendicular to the trajectory (hence, the name normal is used) and lies in the vertical plane containing the trajectory. Without being exact, it might be said that the normal direction indicates whether the missile is above or below the correct path. When a normal error exists, the

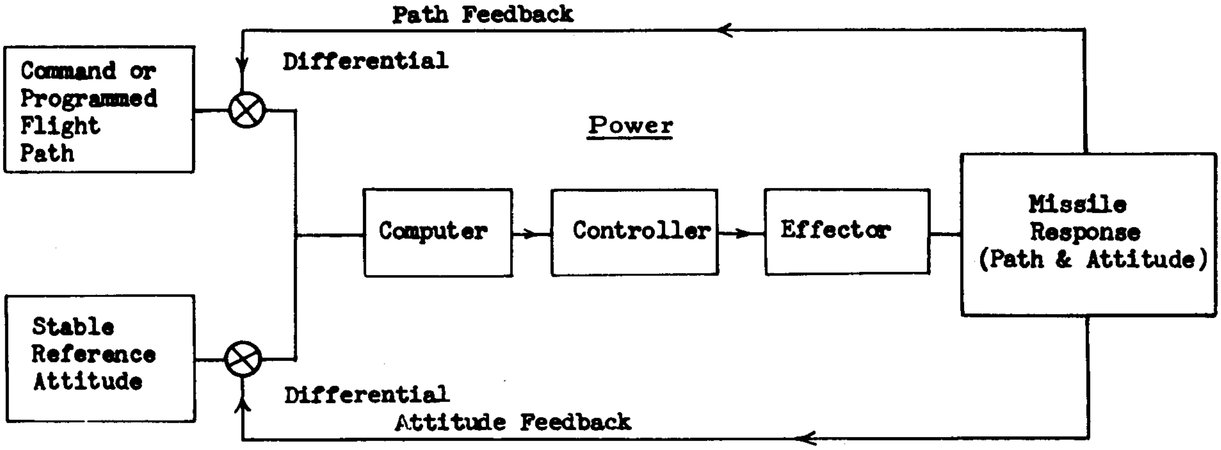


Fig. 5-3 Complete missile guidance system.

missile pitches and brings it back to the path. It may be seen then, that pitch attitude control and normal path control are closely associated.

(c) The range direction is simply distance made good from the launcher to the target. There is no association between roll attitude and range direction.

The proper flight path required to hit the target may be either programmed into the missile prior to launch, or given to the missile in the form of commands emanating from an outside source during flight. The actual path that the missile is following may be determined from outside tracking, or internally mounted sensing devices.

In a complete guidance system the computer, controller, and effectors, used for path control, are generally the same components which are used in the attitude control system. A representative missile guidance system is shown in Figure 5-3.

5-4 GUIDANCE FOR PREDETERMINED TRAJECTORIES

The following basic guidance systems are associated with surface-to-surface and air-to-surface missiles where a fixed trajectory of the missile is predetermined prior to launch.

5-4.1 PRESET GUIDANCE SYSTEM

In a preset guidance system, path control signals or directions are generated in a predetermined time sequence by a device within the missile. This time sequence is determined before missile launch, and it cannot be adjusted once the missile has taken off. In flight, various functions are performed which should keep the missile on its prescribed path to the target. However, if any component does not function perfectly, the missile probably will not hit the target.

An example of the use of a preset system was that of the V-2 rocket, where gyroscopes were used to supply the signals to the control system to actuate the external fins and the jet vanes, so that the missile would follow a predetermined trajectory. Fuel cut-off was accomplished by an accelerometer when the missile reached a velocity sufficient to carry it on a free flight path to the target. The firing procedure for the V-2 was first to locate the coordinates of the target and the launching site on a map, and then to erect the missile at the launcher with its lower side

(bottom fin in flight) pointing toward the target. The missile was fired vertically and was set to tilt at a specific angle from the vertical at the end of a given time; the motor continued to accelerate the missile along the path of this angle until the particular velocity for a specific range was reached; then the motor was cut off. From then on, the missile acted like an artillery shell in flight, following a ballistic path dependent on the line of motion of the missile, the speed of the missile, and the height of the missile at fuel cut-off.

At the present time there is no surface-to-surface missile either operational or contemplated which employs this type of guidance system for midcourse or terminal guidance due to its inherent poor accuracy; but, this system may be effectively used for the initial guidance phase. This type guidance system has inherently poor accuracy because it is "open loop" in nature. Since there is no feedback or comparison of the resultant path with the programmed path every component must function perfectly if the desired result is to be attained. In physical equipment this is indeed quite rare.

5-4.2 TERRESTRIAL REFERENCE GUIDANCE SYSTEMS

A "terrestrial reference system" is a missile guidance system for a predetermined path. A programmer is used to reference the path of the missile to phenomena on the earth and in its surrounding medium (such as atmospheric pressure, density, temperature, magnetic field, electric field, gravitational field, topography, etc.). The path of the missile can be adjusted after launch by devices in the missile which measure one or more of the above parameters; compare the measured data with programmed data; and send error signals to the control system until the proper value of the proper parameter is attained.

One of the most simple, yet practical illustrations of this system is the German V-1. This missile's course was monitored by a magnetic compass placed in the nose of the missile. If the buzz bomb turned to the right or the left, the compass created an error signal which directed its control system to bring it back on course. The V-1 maintained its altitude by measuring air density. It compared the measured air density to a programmed air density representing the desired altitude. If a difference existed, the device initiated the necessary action to move the missile higher or lower. The range was set on an air log similar to a speedometer connected to a small propeller.

A system of radar map matching using the configuration of the earth's surface as a reference is a type of terrestrial reference system. This system is limited to surface targets and requires accurate radar definition and photography, as well as topography data prior to launch. Recent developments in this field have demonstrated the practicability of providing a standard guidance system for very long-range missiles and aircraft. Applications of the techniques described should appear in missile systems within the next several years.

5-4.3 RADIO NAVIGATION GUIDANCE SYSTEMS

A radio navigation guidance system is a system wherein the predetermined path of the missile can be maintained after launch by the time or frequency measurements of radio signals. There are many variations and types of guidance systems utilizing radio signals; however, only one general type with several ramifications will be covered in this text.

Radio waves travel at the speed of light. Since this speed is known and the length of time required to send radio signals from one point to another can be measured, then the distance between the two points can also be determined. Figure 5-4 illustrates two possible courses a missile might follow using radio navigation for guidance. The missile in Figure 5-4 (a) flies a straight line path by comparing the time of arrival of pulses that are transmitted simultaneously by radio stations at $R1$ and $R2$. If the pulses arrive at the same time, the range from the missile to $R1$ will be exactly equal to the range from the missile to $R2$, and the missile will fly along a straight line. In Figure 5-4 (b) the missile transmits pulses to a radio station at $R1$. As soon as each pulse arrives at $R1$, it is immediately transmitted back to the missile. The missile measures the time it takes a pulse to travel to $R1$ and return, and thus measures its distance from $R1$. The missile then flies a course such that this radio time, and hence the distance

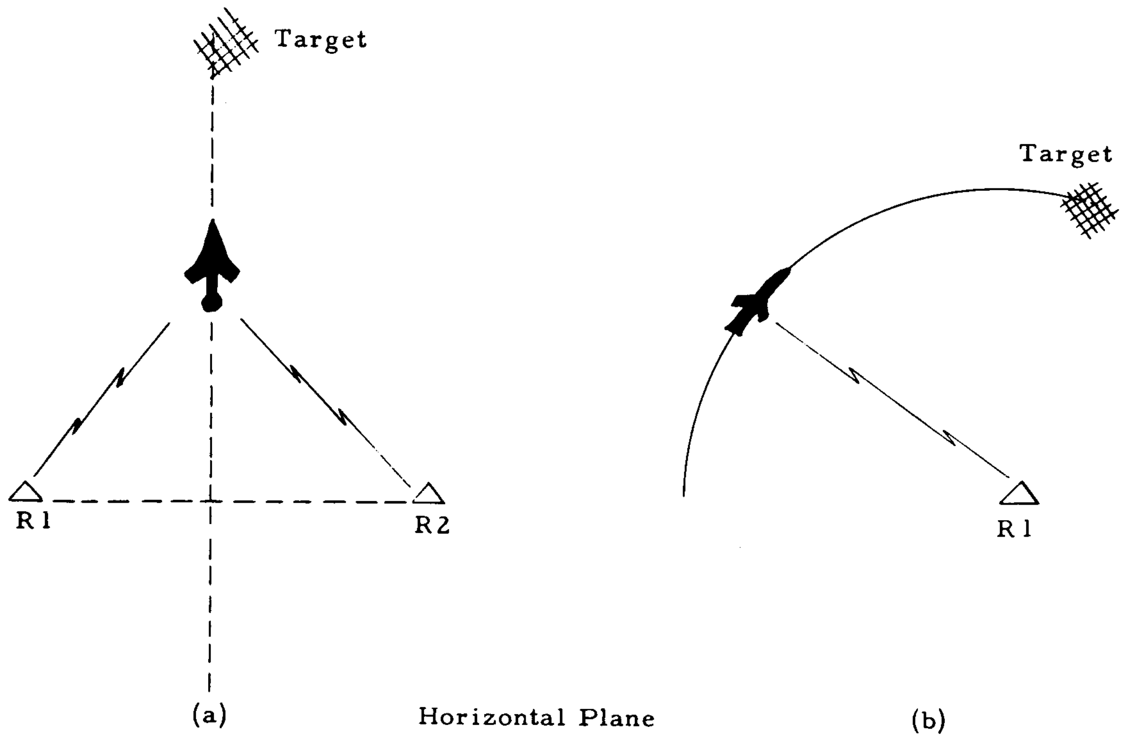


Fig. 5-4 Radio navigation paths.

from $R1$, is always kept constant. The path the missile flies will be a circle.

Although radio navigation may be used for circular or straight line courses, the most important application of radio navigation for guided missile use involves hyperbolic paths. When a hyperbolic path is flown by a missile, the missile will always be a fixed distance farther from one guidance station than from the other. Figure 5-5 shows a grid of hyperbolas. The group of hyperbolas indicated by the solid lines is determined by radio stations $R1$ and $R2$. The group of hyperbolas illustrated by dotted lines is determined by radio stations $R3$ and $R4$. A missile flying along the heavy solid line hyperbola that passes over the target may always be located one mile farther from $R1$ than from $R2$. The missile computer causes the missile to fly along a hyperbolic path (heavy solid line) by comparing the arrival time of pulses transmitted simultaneously by $R1$ and $R2$. The missile also listens to pulses being transmitted by $R3$ and $R4$, which determine another hyperbola (heavy dotted line) that passes through the target. When the difference in arrival time, heard by the missile, indicates that the missile is crossing the heavy dotted line, and hence, over the target, signals are sent to the missile control surfaces to cause it to pitch over to impact.

In order to obtain high accuracy with radio navigation in guided missiles, very high radio frequencies (VHF) are used. At these frequencies (over 30 megacycles) radio waves are propagated on a straight line from the transmitter and do not curve around the earth. Therefore, as the range from the transmitter increases, the curving surface of the earth drops away from the straight line radio horizon. At a range of 250 miles the radio horizon is 31,000 ft above the earth's surface. Although long distance radio transmission is dependable in the very low frequency region (10 to 100 kilocycles), the efficiency of any antenna carried on a supersonic missile would be infinitesimal at these frequencies. It therefore may be seen that a missile employing a radio navigation guidance system is limited in range.

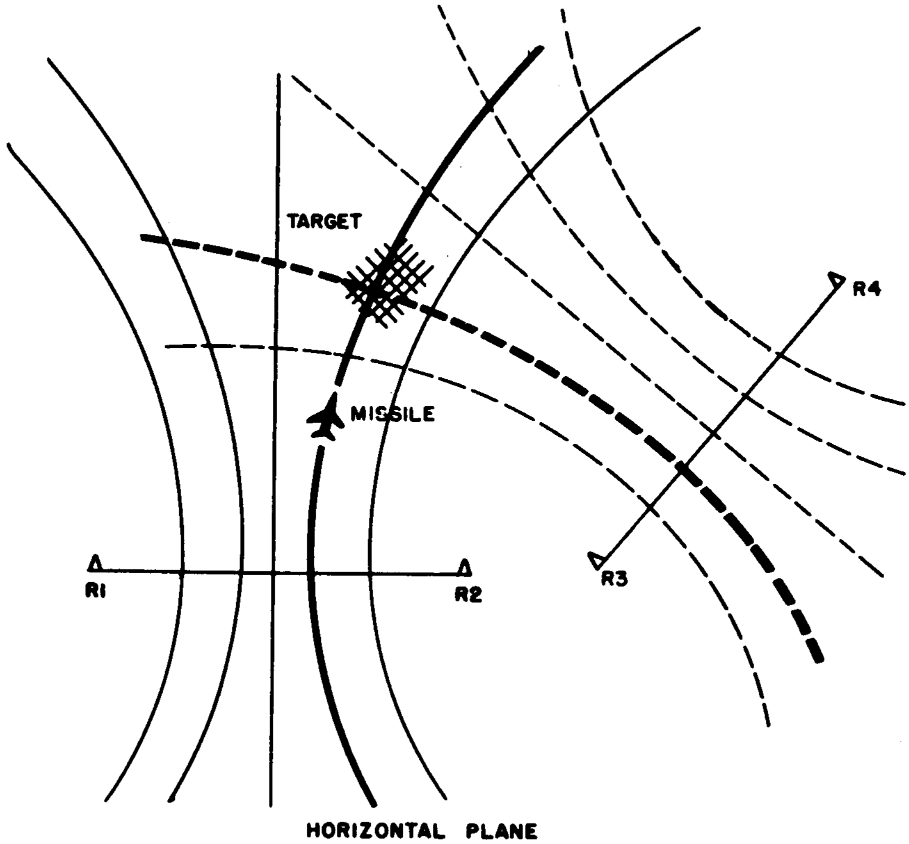


Fig. 5-5 Hyperbolic grid.

5-4.4 CELESTIAL NAVIGATION GUIDANCE SYSTEM

A celestial navigation system is a guidance system wherein the predetermined path of the missile can be maintained during flight by the use of continuous celestial observation. This system is based on the known apparent position of celestial bodies with respect to points on the surface of the earth at a given time. Since the location of the launching point, the target, and the identity of the stars to be used are known before launching, any position on the surface of the earth can be determined from observations on these stars by measuring their azimuth angles and angles of elevation above the horizon with reference to time.

In a guided missile the horizontal reference is determined by a stabilized platform which is maintained perpendicular to a hypothetical line from the missile to the center of the earth, by gyroscopes and accelerometers. Automatic star tracking telescopes make the "fixes" on the stars, and signals proportional to the measured star angles at a given time are then sent to a computer, which compares this actual data with programmed data. The programmed data includes the star angle information for the same instant of time that the missile should reproduce if it is to proceed along the proper path. Deviations determined by the computer between the actual measured data and the theoretical programmed data produce error signals which are sent to the path control system for correction of the missile path (Figure 5-6).

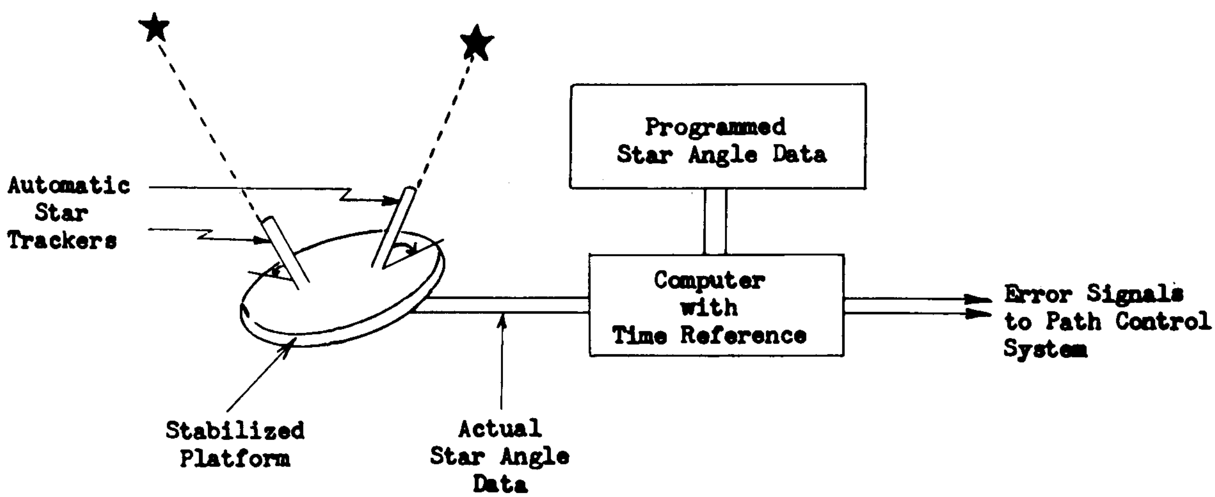


Fig. 5-6 Schematic of celestial navigation guidance.

In order to be effective the systems must be able to track stars in the daytime as well as night. This has been accomplished with very sensitive photoelectric cells.

5-4.5 INERTIAL GUIDANCE SYSTEM

An inertial guidance system enables a missile to follow a predetermined path by the employment of sensitive accelerometers within the missile which make use of the principle of Newton's second law of motion, $F = ma$. An accelerometer is a device which measures accelerations with reference to a stabilized platform. Gyroscopes and accelerometers are utilized to keep this stabilized platform perpendicular to a line from the missile to the center of the earth. In an inertial guidance system, accelerometers detect accelerations both along the predetermined flight path and perpendicular to it. This information is furnished to a computer which doubly integrates the acceleration as a function of time and determines distance, since

$$\text{distance, } S = \int \int a\, dt\, dt$$

If a missile is launched on a course toward a target, it will remain on this course until acted on by an outside force. When this outside force (such as a gust of wind) acts to change the course of the missile, an acceleration will be experienced by the missile. The accelerometer within the missile will detect this acceleration. This signal is sent to a computer which doubly integrates it, and determines an error signal which is sent to the path control system as a distance off course. The control system of the missile will react to the error signal and move the missile this same distance back on course. The accelerometers meanwhile detect this second acceleration, the computer doubly integrates it, and when the missile gets back on course, no error signal exists. The missile then continues on straight line flight until another error is introduced.

Accelerometers are also used for range control. As the missile accelerates from zero velocity to its cruising speed, the accelerometer measures the acceleration, and the computer converts the acceleration to distance covered along the path of the missile. When the missile reaches cruising speed and the acceleration is zero, the computer computes distance covered on the ground by multiplying velocity times time. If the missile changes velocity along the path, an acceleration or deceleration will be observed by the range accelerometer and the computer will determine distance by doubly integrating this signal. When the proper range has been covered, as programmed into the missile prior to launch, the computer sends a signal to the control system to dive the missile into the target (Figure 5-7).

Although relatively simple in concept, the development of an operational inertial guidance system presents many problems in order to attain required accuracy. Some of the most serious

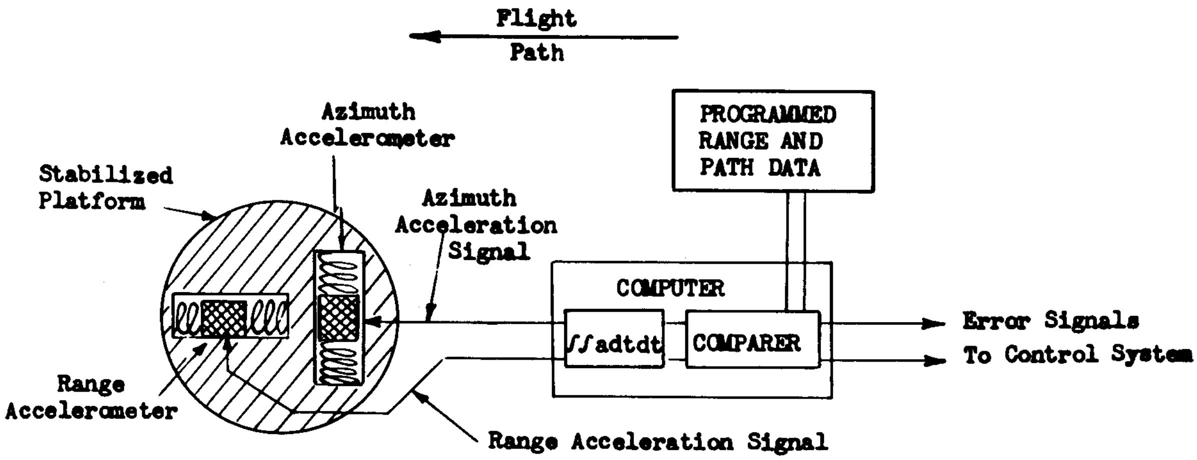


Fig. 5-7 Schematic of inertial guidance system.

problems are:

(a) A missile in flight is subjected to centrifugal force due to rotation of the earth as well as the force of gravity. This makes it difficult in attaining a true vertical for the stabilized platform.

(b) A missile in flight is subjected to a distorting force resulting from rotation of the earth called Coriolis force.

(c) Friction in the bearings of the gyroscope gimbals produces torques which cause the gyroscopes to precess causing deviations in the stabilized platform. The magnitudes of these deviations are not always predictable.

An inertial guidance system appears to be the most promising type of guidance for long-range missiles. It is particularly well suited for long-range ballistic type missiles since the time of the guided portion of the flight is quite short. The accumulation of errors will therefore be very slight.

5-5 GUIDANCE FOR CHANGING TRAJECTORIES

The following guidance systems are associated with surface-to-air, air-to-air, and short-range surface-to-surface missile systems where the missile is launched toward the general location of a moving target and is guided to contact or close proximity to an evasive target for a kill.

5-5.1 COMMAND GUIDANCE SYSTEM

A "command system" is a guidance control system wherein the path of the missile can be changed after launch by directing signals from some agency outside the missile. Information as to the relative position of the target and the missile is furnished to a computer on the ground which solves the intercept problem and sends commands to the missile to direct it to intercept the target. The missile will follow an intercept trajectory determined by the navigational method designed into the computer.

One of the simplest basic approaches to the problem is the system used to guide a drone plane into a target. A human operator observes the drone and the target, estimates the changes required in the drone's flight path, and sends radio signals to the drone which, through a suitable control system, executes the desired maneuver. In a more advanced typical surface-to-air system, the human operator is replaced by two radars and a computer (Figure 5-8). One

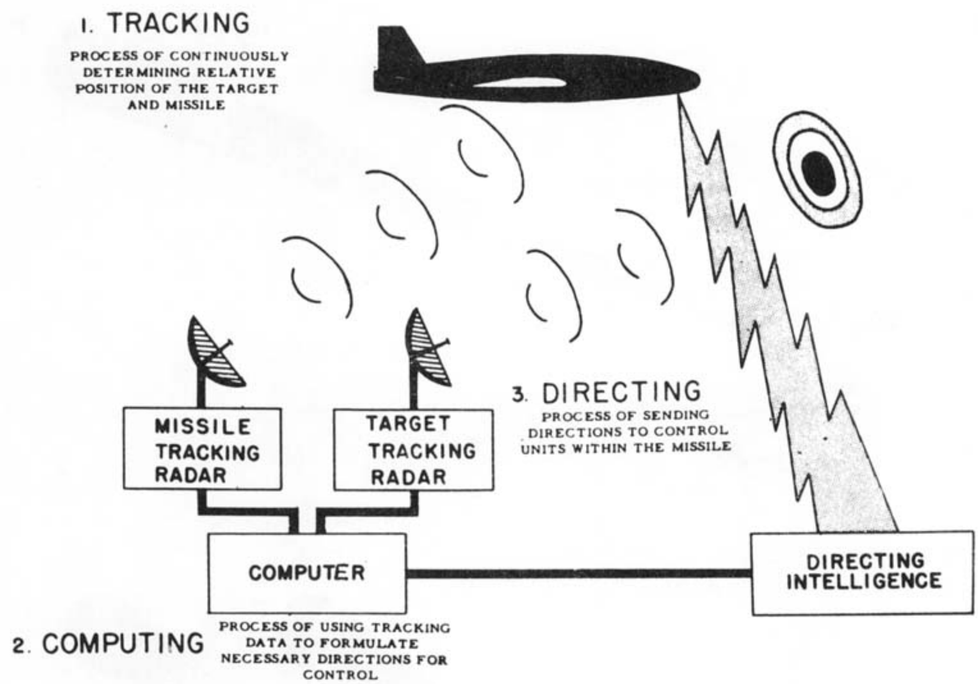


Fig. 5-8 Command guidance system.

radar tracks the target; the other the missile. The computer continuously compares the path of the missile and the target and continuously solves the intercept problem. New direction headings are sent to the missile, either by the missile tracking radar or by a separate radio link. This type command system is being successfully employed for surface-to-air missiles, such as the operational NIKE missile system. Another application of command guidance is for air-to-surface missiles where a similar system may be employed.

Still another application of the command system is for surface-to-surface missiles. In this case the location of the target is known, which fixes the flight path the missile is to follow. A radar tracks the missile comparing its actual flight with the desired path and transmitting necessary corrections. This system is somewhat limited in range due to line-of-sight requirements of radar.

5-5.2 BEAM RIDER

A "beam rider system" or line-of-sight system is a guidance control system wherein the direction of the missile can be changed after launching by devices in the missile which keep the missile in a beam of energy. Radars produce the most promising types of beams for this system; however, other energy beams such as light and heat might be used for this purpose. In applying the radar technique to the guidance of a surface-to-air missile the beam of the target-tracking radar would have to be so modified that adequate information is conveyed to the missile for it to determine where it is with respect to the center of the beam and guide itself toward a predetermined position within the beam (Figure 5-9). A beam rider system is limited to short ranges because accuracy decreases as the beam width increases.

One variation of the beam rider system is called the modified or dual-beam rider (Figure 5-10). In this system the missile-carrying radar beam is positioned by another target-tracking radar and computer combination. The modified beam rider system is conceived to surmount the problem of excessive transverse accelerations encountered by the beam climber in flying a continually changing line-of-sight course to the target. This occurs because the beam is constantly pointing directly at the target and moving with the target. In the modified beam rider system, it is contemplated that two radars and a

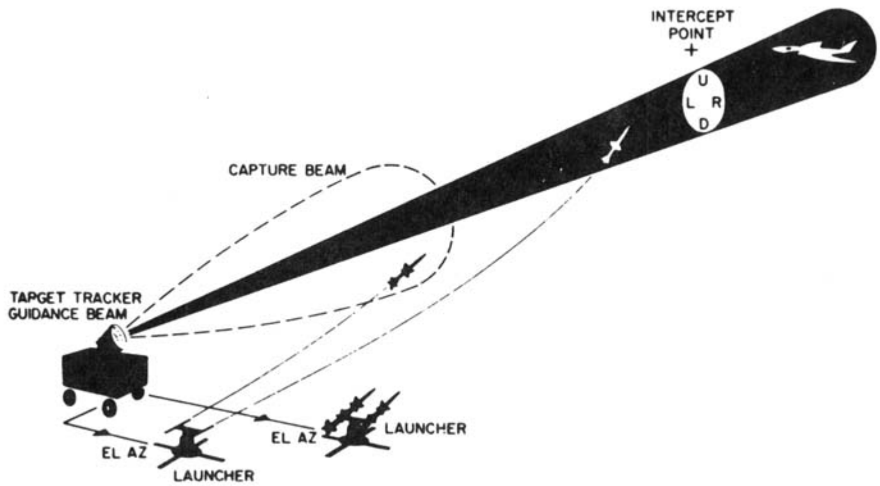


Fig. 5-9 Single-beam rider.

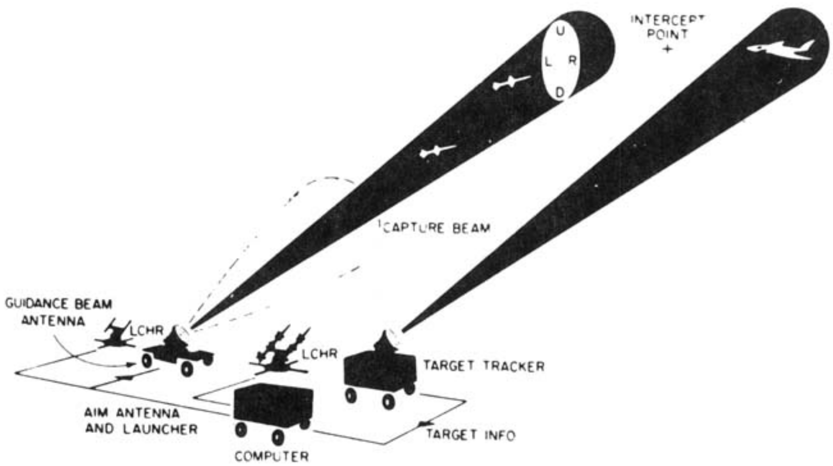


Fig. 5-10 Dual-beam rider.

computer will be used. The target-tracking radar feeds target data into the computer which calculates a predicted position of the target based on target data and missile data. The second radar is pointed toward the predicted point and the missile follows this beam. This beam also supplies missile data to the computer.

The modified beam rider system is a variation of the command system in which the commands are transmitted to the second radar instead of to the missile. The missile obeys these commands by virtue of its beam riding equipment. This system is more effective against maneuvering targets than the normal single beam rider system. Also, it would be easier to launch a missile into a second beam than to launch the missile into the beam that was tracking the target. These advantages may be offset by the additional ground equipment required over that used in the single beam rider system.

5-5.3 HOMING (TERMINAL GUIDANCE)

A "homing system" is a guidance control system wherein the direction of the missile can be changed after launch by a device in the missile which reacts to some distinguishing characteristic of the target. A homing guidance system may be used as the primary guidance for a guided missile or it may be used in conjunction with another type of guidance system. When used

with another system, homing generally accomplishes the guidance for the terminal or final phase of the missile trajectory. Homing guidance is used for both fixed trajectories and changing trajectories.

Basically, a homing system consists of a seeker in the missile which automatically keeps pointed at some special characteristic of the target, and feeds data into a computer to keep the missile headed so as to hit the target. The important target characteristics which have been studied as means of perceiving the target are:

(a) Light emissions.
(b) Radio emissions.
(c) Radar reflectivity.
(d) Infrared emissions.
(e) Sound emissions.
(f) Capacitive features.
(g) Magnetic features.
(h) Radioactivity.

Of these characteristics, the best means of detecting targets to date are infrared radiation and radar signals. These systems are sufficiently accurate to assure a high target kill probability within their range of operation. The main drawback is range limitation in that the limit for infrared is 2 to 3 miles and for radar about 10 miles. This limits homing, in some applications, to the terminal guidance phase, one of the systems discussed above being used for mid-course guidance.

Homing systems can be subdivided into active, passive, and semi-active depending on their method of operation. An active homing system is one wherein the source of illumination of the target as well as the receiver is in the missile (Figure 5-11). A passive homing system is one wherein the receiver in the missile utilizes natural radiations from the target as in the case of heat radiations from a ship or factory (Figure 5-12). A semi-active homing system is one wherein the receiver in the missile utilizes radiations from the target which has been illuminated from some source other than the missile (Figure 5-13). All of these types are currently under development with certain types best for a given target; for example, the passive system for infrared seekers and the active or semi-active for radar seekers.

Homing seekers used in antiaircraft or antimissile systems are sometimes classified according to the type of navigational course the missile flies. Any one of the common types of navigational courses, pursuit, constant bearing, or proportional, could be incorporated into a homing guidance system.

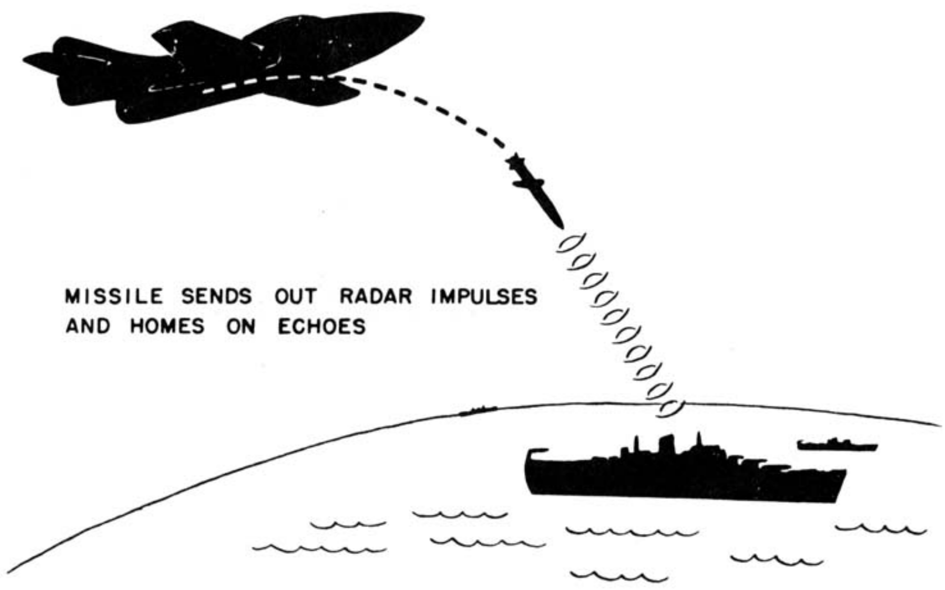


Fig. 5-11 Active homing.

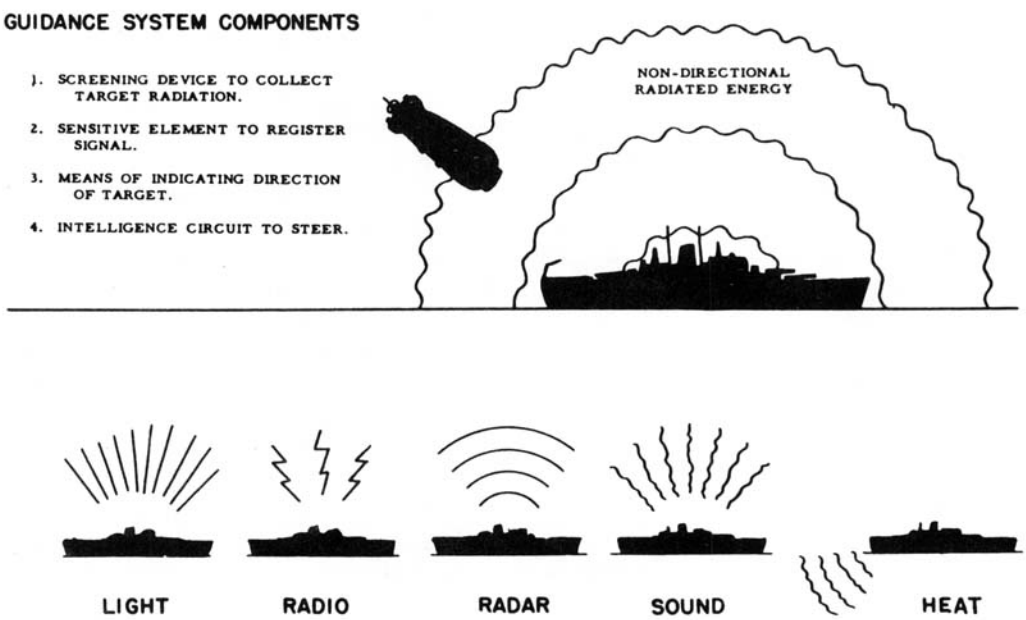


Fig. 5-12 Passive homing guidance.

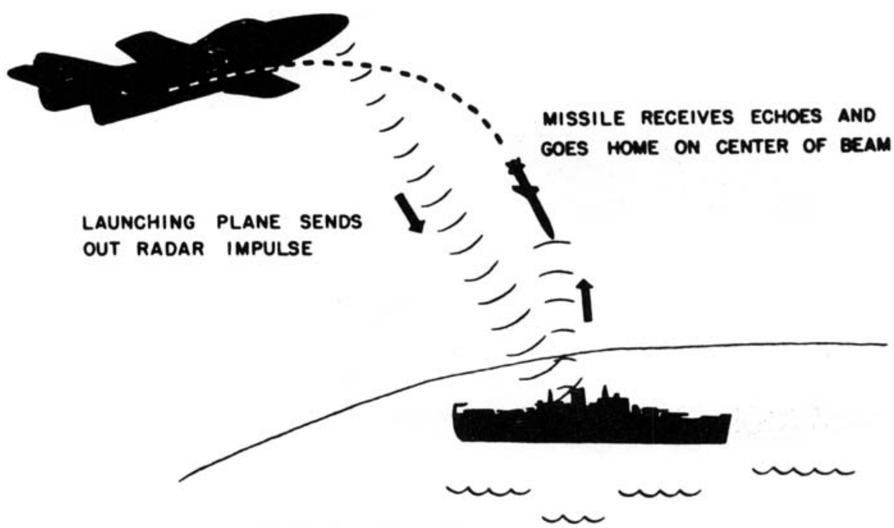
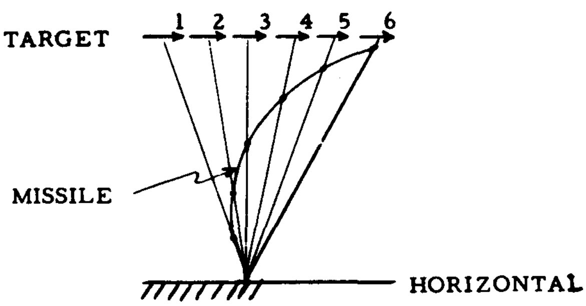


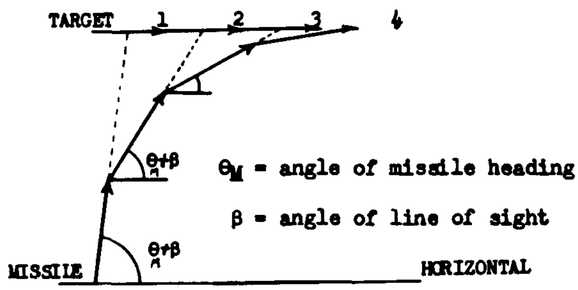
Fig. 5-13 Semi-active homing guidance.

5-6 KINEMATICS OF INTERCEPT COURSES

A command signal to the missile can direct the missile toward the target by various intercept paths. The specific intercept path employed is designed into the computer and therefore is an inherent characteristic of the missile system. Four of the five most common navigational methods for solving the intercept problem are as follows:

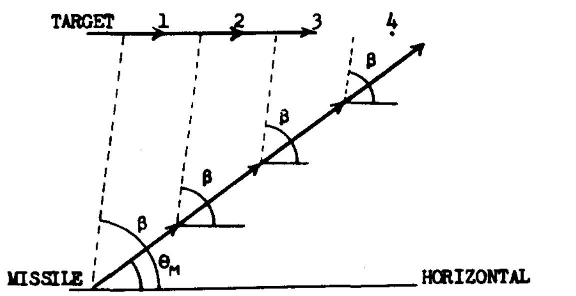


(a) Line of sight. Defined as a course in which the missile is guided so as to remain on the line joining the target and point of control.



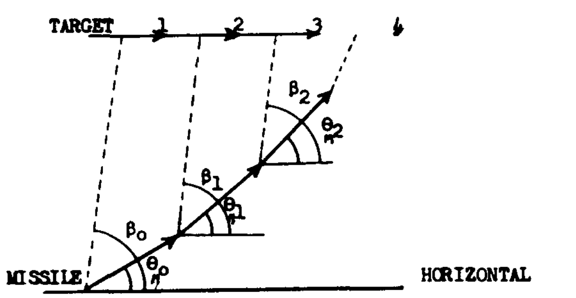
(b) Pursuit. Lead or deviated pursuit course is defined as a course in which the angle between the velocity vector and line of sight from the missile to the target is fixed. For purposes of illustration, lead angle is assumed to be zero and only pure pursuit is described

$(\theta_M = \beta)$.



(c) Constant bearing. A course in which the line of sight from the missile to the target maintains a constant direction in space. If both missile and target speeds are constant, a collision course results

$$\left(\frac{d\beta}{dt} = \dot{\beta} = 0\right).$$



(d) Proportional. A course in which the rate of change of missile heading is directly proportional to the rate of rotation of the line of sight from the missile to target

$$\left(\frac{d\theta_M}{dt} = K\frac{d\beta}{dt} \quad \text{or} \quad \dot{\theta}_M = K\dot{\beta}\right).$$

The problem of analysis of flight paths must be solved in the design stage in order to observe the characteristics of trajectory, time of flight, maximum rate of turn, and maximum lateral acceleration for a proposed system, in terms of anticipated target maneuvers, relative speeds of missile and target, and motion of point of control. Once a system is determined, the computer solves the specific problem for each encounter. Accuracy being vital to the kill probability, the inherent speed and accuracy of digital computers for this purpose has speeded their development to the point of being competitive, and subsequently superior, to analog computers for this purpose.

Before any of these methods can be analyzed it will be necessary to understand the geometry of the problem (Figure 5-14). Only two-dimensional motion will be considered, but it must be realized that the problem is a three-dimensional one.

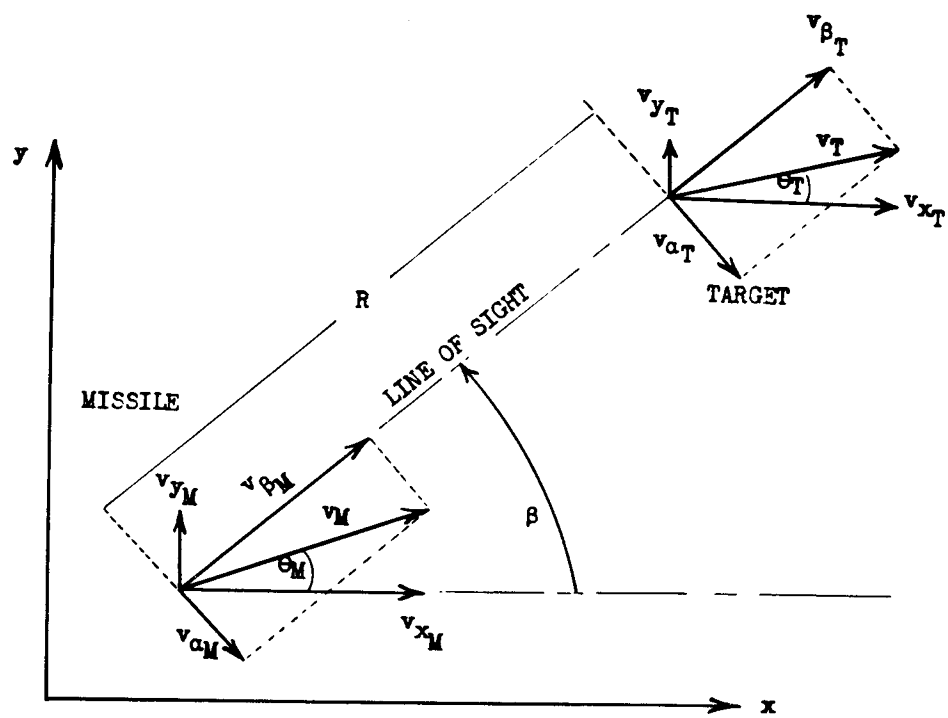


Fig. 5-14 Geometry of intercept problem.

In Figure 5-14:

θ is angle of heading

β is angle of line of sight

R is range or distance between missile and target

v is velocity vector

γ is ratio of missile velocity to target velocity, $\left(\gamma = \frac{v_M}{v_T}\right)$

subscript M refers to missile.

subscript T refers to target.

subscript β refers to direction along line of sight (LOS).

subscript α refers to direction perpendicular to line of sight.

Several relations between the parameters of the problem are now observed.

The range R, at any given time:

$$R = \int_0^t (v_{\beta_T} - v_{\beta_M})\ dt + R_{initial} \qquad (5\text{-}1)$$

Interception will take place only if R is always decreasing and for R to decrease

$v_{\beta_T} - v_{\beta_M} < 0$, or negative.

From Figure 5-14 the following relations may be determined:

$$\begin{aligned}\frac{dR}{dt} = \dot{R} &= v_{\beta_T} - v_{\beta_M} \\ &= v_T \cos(\theta_T - \beta) - v_M \cos(\theta_M - \beta) \\ &= v_M \left[\frac{1}{\gamma}\cos(\theta_T - \beta) - \cos(\theta_M - \beta)\right]\end{aligned} \qquad (5\text{-}2)$$

and

$$\begin{aligned}\frac{d\beta}{dt} = \dot{\beta} &= -\frac{v_{\alpha_T} - v_{\alpha_M}}{R} \\ &= -\frac{v_T \sin(\theta_T - \beta) - v_M \sin(\theta_M - \beta)}{R} \\ &= -\frac{v_M\left[\frac{1}{\gamma}\sin(\theta_T - \beta) - \sin(\theta_M - \beta)\right]}{R}\end{aligned} \qquad (5\text{-}3)$$

The characteristics of the four navigational methods follow.

(a) Line of sight (beam rider). A beam rider always flies the line of sight from a tracker on the ground to the target and requires associated ground equipment which may be jammed. However, new developments such as pulse-doppler radar, may effectively counter the enemy's jamming ability. Turning rates are always finite when $\gamma > 1$, hence, lateral accelerations must be determined as functions of altitude, range, relative missile velocity, and angle of line of sight, B.

(b) Pure pursuit. The missile is always headed toward the target along the line of sight:

$\theta_M = \beta$, then $v_{\beta_M} = v_M \cdot \theta_M = \beta \rightarrow \theta_T$,

in other words, interception takes place from the tail of the target (unless the target is met head on). The missile must maneuver but the pursuit course is the simplest to mechanize in a guidance system. With pure pursuit navigation the lateral acceleration of a missile attacking a non-maneuvering target will be infinite at the instant of intercept if the missile velocity is more than twice the target velocity. The lateral acceleration will be zero at the instant of intercept if the missile velocity is less than twice the target velocity.

From these conclusions, it is realized that unless some miss distance is allowable, it is impractical to use a pursuit course when the missile velocity exceeds twice the target velocity, since it is impossible for a missile to attain an infinite lateral acceleration.

(c) Deviated pursuit. A deviated pursuit course, often referred to as fixed lead navigation or constant bearing navigation, is a course in which the angle between missile velocity vector, V_M and line of sight $(\theta_M - \beta)$ is fixed. Thus, if $\delta = \beta - \theta_M$, (5-2) and (5-3) become, respectively

$$\dot{R} = V_T \cos\beta - V_M \cos\delta \qquad (5\text{-}4)$$

$$\dot{\beta} = -\frac{V_T \sin\beta - V_M \sin\delta}{R} \qquad (5\text{-}5)$$

Figure 5-15 shows a plot of the relationship between γ and $\sin\delta$ which must exist in order that $\dot{\beta}$ remain finite (Region II) or zero.

It is seen that only for $1 = \gamma \leq 2$ will it be possible to select a δ which does not yield an infinite turning rate. Of course in practice, when turning rates called for are in excess of the maximum missile turning rate, the missile will remain in its maximum turn until it cuts across the line of the target path and then re-enters the proper course or is lost. Since lateral acceleration, $a_M = V_M\,\dot{\beta}$, characteristics of turning rate apply to lateral accelerations when V_M is constant.

(d) Constant bearing. The missile is navigated so that the target always has the same bearing, $\frac{d\beta}{dt} = \dot{\beta} = 0$. For a nonmaneuvering target moving with constant velocity, this means that a missile with constant velocity will ideally be directed onto a straight-line collision course. A perfect constant bearing course is impossible to attain in an actual system, however, due to inherent system errors and dynamic lag.

A constant bearing course is utilized for the antiaircraft artillery fire control problem, where

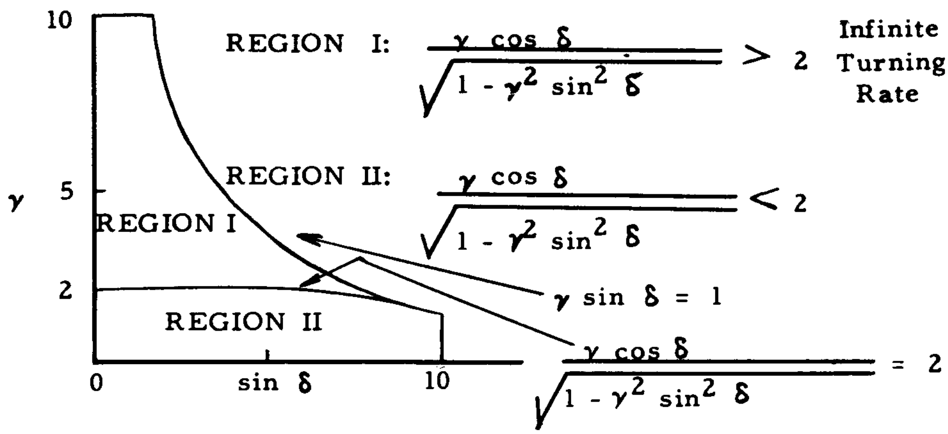


Fig. 5-15 Conditions for finite turning rate (deviated pursuit).

the computer determines θ_M, the direction to point the guns in order to accomplish intercept. This method is not satisfactory for use with guided missiles.

(e) Proportional. The angular velocity $\dot{\theta}_M$, of the missile is a constant K, times the angular velocity, $\dot{\beta}$ of the line of sight; $\dot{\theta}_M = K\dot{\beta}$. Hence, $\theta_M = K\beta + \theta_o$.

Both pursuit and constant bearing navigation methods are special cases of proportional navigation. For example:

When $K = 1$ and $\theta_0 = 0$, $\theta_M = \beta$, which is pursuit navigation.

When $K = \infty$, then $\dot{\beta} = \frac{\dot{\theta}_M}{\infty} = 0$, which is constant bearing navigation.

It could be shown that for a maneuvering target and a variable speed missile, the required missile rate of turn, $\dot{\theta}_M$, is always finite when $K \geq 4$. Considering a realistic interception problem, proportional navigation is probably the most satisfactory, although the computer setup will be more complex than for a pursuit or constant bearing course. Most operational and developmental air defense guided missile weapon systems, employing command or homing guidance system, are designed with some type of proportional navigation.

REFERENCES

Locke, A. S., *Principles of Guided Missile Design*, D. Van Nostrand Co., Inc., Chapter 12.

CHAPTER 6

INTRODUCTION TO TERMINAL BALLISTICS

6-1 SCOPE

Terminal ballistics is concerned with the principles underlying the effects of weapons on targets to include penetration, fragmentation, detonation, shaped charge, blast, combustion, and incendiary effects.

In designing weapons and ammunition, maximum desired terminal effect is a primary objective. A proper balance of many factors is essential to accomplish this purpose. The most important of these factors are shape, weight, and material used in the projectile; type and weight of explosive charge; fuzing system; and terminal velocity. Data on performance as influenced by these factors, with the exception of fuzing, are discussed in this section of the text.

6-2 DEVELOPMENT AND USE OF TERMINAL BALLISTICS

The science of terminal ballistics has lagged behind the companion sciences of exterior and interior ballistics primarily because of difficulties in obtaining basic data for study. Rapid advances in the fields of radiography and high speed photography have relieved the situation somewhat, but the problem of securing good data remains complex. For example, direct observation of the end product is possible only in fragmentation studies. Mechanisms by which these results were achieved can be determined only by statistical analysis of fragment distribution. However, new developments and improvements in recording techniques are helping to increase our knowledge of the subject.

Studies previously initiated were intensified during World War II and are now being continued for the purpose of accumulating a greater store of technical data pertinent to terminal ballistics. Much of this data, relating to the performance of ammunition and the vulnerability of targets, has been published in a wide variety of documents for the benefit of both the ammunition designer and consumer. This has been of real value to combat unit personnel who plan and direct the application of firepower. In the final analysis, it is the responsibility of commanders or staff officers to select the proper ammunition from among the many types placed at their disposal by the technical services; it is also the commander's responsibility to use it properly. It is hoped that an appreciation of the principles to be brought out in this text will impress the student with the essential economy involved in a terminal ballistic viewpoint; economy of effort, time, materials, and manpower.

6-3 TECHNIQUES OF TERMINAL BALLISTIC STUDIES

Because terminal ballistic effects ordinarily appear as instantaneous events to the layman, the time factor in terminal ballistic investigations has often been the limiting factor; i.e., the ability to physically record detailed reactions which take place during time intervals of the order of several microseconds.

Experiments are conducted to determine the principles governing the number, size, velocity, and spatial distribution of fragments (Figure 6-1) resulting from detonations of cased high explosive charges, in order to gain knowledge

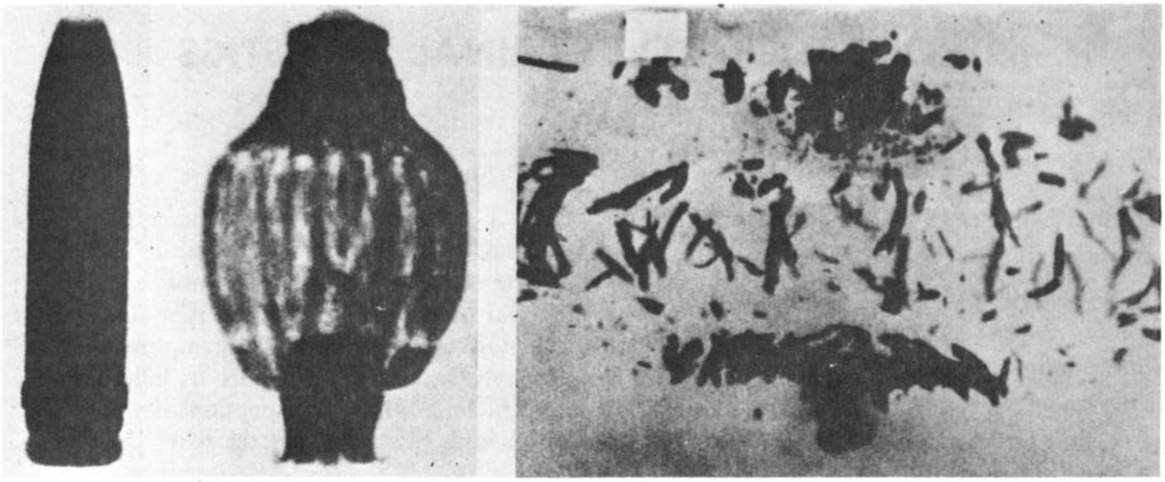


Fig. 6-1 Bursting shell.

that will permit optimizing of effects on enemy targets. Thick wall enclosed chambers, instrumented optically and electrically, and lined with thicknesses of materials to trap fragments are basic to these investigations. Penetration effects of small missiles and fragments demand knowledge of air drag parameters of fragments and sub-missiles.

Investigations concerning the production and prevention of fire damage to military materiel must be conducted concurrently. The physical nature of the detonation process within explosives involves studies of detonations by various types of initiators with physical measurements by use of X-ray, electrical, and optical techniques. Detonation studies include the mechanism for the formation of air shock from explosions.

Studies of the propagation and effects of shock waves in earth, rock, air, and other gases under varying conditions are required for the design of blast producing weapons, and for the design of structures capable of withstanding the effects of such weapons. The effects of detonation of small charges under varying conditions are found from actual experiments. Extrapolations are made by appropriate scaling laws to obtain effects of full scale weapons. The studies of blast waves extend from the surface of an explosive to extended distances, and include studies of effects against personnel, structures, structural members, aircraft, and the air-blast coupling into the ground for relatively long durations. In addition to the timing devices and sensitive pressure pickups, a basic technique involves large shock tubes to reproduce shock wave forms that can be scaled accurately to represent types of shock fronts that result from both conventional and atomic explosions (see Figure 6-2).

The study of shaped charge and high velocity jets involves investigations in a variety of scientific fields. These include the physics of plasticity of metals at very high strain rates; the physics of interactions between metals and high explosives; and the field of instrumentation design for highly specialized applications. Included are multiple flash radiographic techniques which produce X-rays of 10^{-7} seconds duration to obtain a series of successive pictures of a jet or collapsing liner. The jet velocity is often in excess of 23,000 feet per second. Optical techniques in shaped charge and detonation studies include rotating mirror cameras, Kerr cells, image convertor systems, Faraday electro-optical shutters, and ultra high speed framing type cameras. These are all directed to record events in terms of exposure time ranging from 1/10,000 to 1/1,000,000 part of a second.

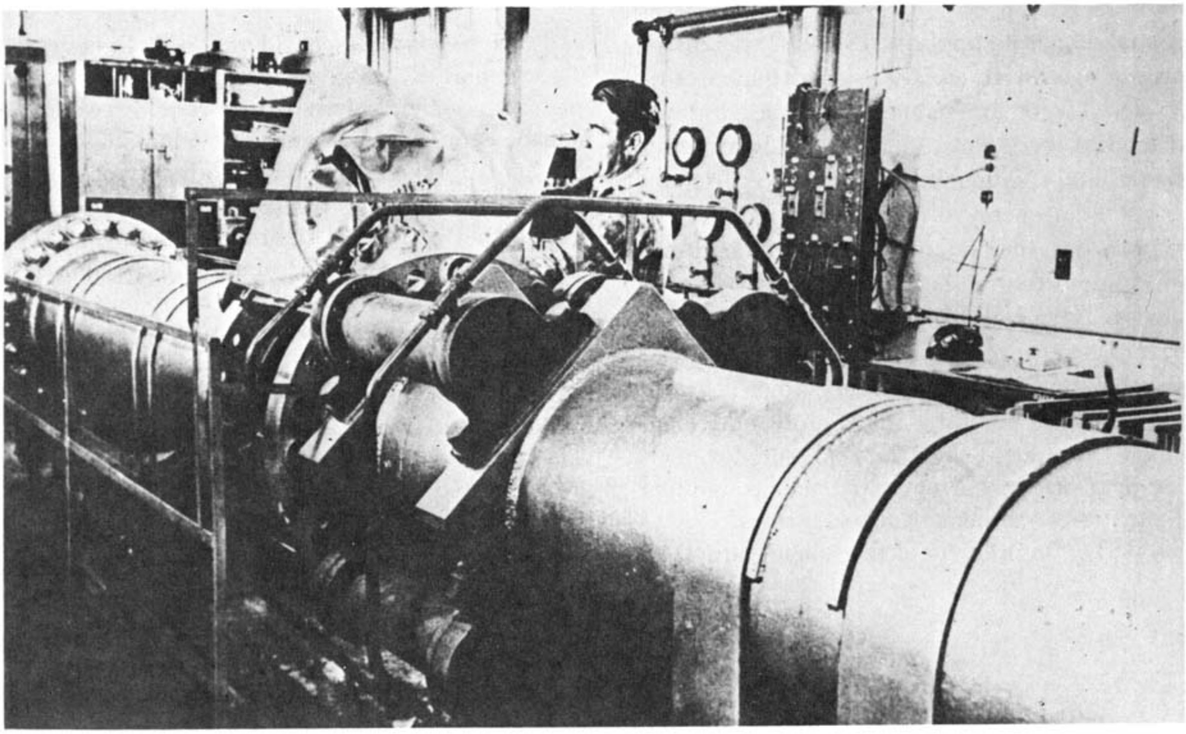


Fig. 6-2 Shock tube.

6-4 MEANS OF PRODUCING DAMAGE

Whatever the type of weapon considered and whatever the nature of the target attacked, damage can be produced by one or more of the physical phenomena associated with the bringing to rest of a missile, with the detonation of an explosive, with nuclear fission, or with chemical or bacteriological action. It is convenient to classify these phenomena as follows:

(a) Fragmentation, or the action of relatively small particles, usually from the case of a bomb, rocket, warhead, or shell.

(b) Impact, which pertains to the penetration or perforation of an object by a relatively large metallic body, such as an armor-piercing shot.

(c) Blast, the effect caused by the sudden release of large amounts of energy in a fluid medium.

(d) Debris, set in motion at relatively high velocities.

(e) Heat, in the flame of the blast, or radiant heat.

(f) Fire, which may result from the effects of an explosive, or may be induced by special incendiary weapons.

(g) Chemical action, particularly from smoke or poisonous gases.

(h) Bacteriological action.

(i) Radioactivity.

6-5 TARGET ANALYSIS

The technical aspects of producing target damage by the many mechanisms described above must include methods or standards by which specific effects on targets can be realized. A target must be considered in terms of its importance to the strategist, the tactician, or the local commander. Its vulnerability may lie in terms of personnel, control equipment on the target, a control center or command post, the logistical lines which supply the target, or the economic

potential which it supports. Likewise, defensive measures against attack at all levels play a critical role. Target intelligence from the strategic and tactical levels must include details of target vulnerability. Vulnerability studies of friendly and potential enemy weapons are highly scientific processes; for example, aircraft vulnerability studies indicate the best hope of kill against enemy planes, and likewise, indicate the most vulnerable areas of our own aircraft which can often be minimized by redesign. Armor is evaluated in terms of mobility, armor protection, main weapon accuracy, and tactical employment. Basic data are concurrently fed into computers for playing of mathematical war games.

Similarly, the problem of the human target extends far beyond the consideration of the effect of one round delivered against an enemy soldier. Incapacitation of enemy troops requires wound ballistic studies which include vulnerability of the human body; effects of body armor; and armament of friendly troops in terms of weight of principal weapon, weight of ammunition carried, weapon accuracy, training time required to reach proficiency with the weapon, and logistical requirements. The optimizing of these parameters may answer such proposals as the arming of the infantryman (in an effort to give him a greater combat effectiveness) with a high velocity rifle of small calibre which will be light, fire accurately at short ranges, and for which he may carry twice or three times the amount of ammunition now prescribed.

6-6 PROBABILITY AND STATISTICAL TREATMENT OF BALLISTICS

6-6.1 INTRODUCTION

Computed trajectories for gun launched projectiles, rockets, bombs, and missiles are based on a rigorous mathematical analysis; accurate data resulting from meticulously instrumented flight tests; and the overwhelming contribution of electronic digital computers to solve the basic equations of motion. The user, however, requires additional fire control data (range and deflection probable error or dispersion data). The designer and the weapons analyst demand performance in terms of hit and kill probability, including all variations resulting from human or systems errors in handling and processing data to the gun or launching device. The following is a brief treatment of the mechanism by which such information is evaluated and used. The total problem is one of statistical analysis which is not only the basis for evaluating these performance parameters, but is the basis for the acceptance and the surveillance of all United States ammunition and other mass produced items under procurement, and in world-wide storage.

6-6.2 PROBABILITY

If a possibilities are each equally likely and if, of the a, exactly b possess some unique attribute, c, then it is said that the probability of c is $\frac{b}{a}$ written

$$P(c) = \frac{b}{a}$$

For example, if, of 10 pencils, 3 are red (let the attribute *red* be denoted by R), 4 are blue (B), 3 are green (G), then the probability of selecting a red pencil at random is:

$\frac{3}{10}$, i.e., $P(R) = .3$

These data may be tabulated thus:

$$R\,R\,R\,B\,B\,B\,B\,G\,G\,G$$

Obviously,

$$P(R \text{ or } B) = \frac{3+4}{10} = .7 = P(R) + P(B)$$

This is known as the *Sum Rule.* Further, the probability of R, B, or G is 1 (or a certainty); whereas the P (yellow) $= 0$ (impossible).

Now, denote hard lead pencils by H and soft by S and retabulate:

$$\begin{matrix} R & R & R & B & B & B & B & G & G & G \\ H & H & S & H & S & S & S & H & H & H \end{matrix}$$

This tabulation tells one that 2 red pencils are hard and one is soft. Thus, if one selects a red pencil, then

$$P(H) = \frac{2}{3}$$

This is known as the conditional probability that a pencil is hard on the hypothesis that it is red, and may be written:

$$P(H|R) = P(H \text{ given } R) = P_R(H) = .667$$

The probability that a random choice will be both red and hard is .2, i.e.

$$P(R, H) = \frac{\text{no. of hard red pencils}}{\text{total no. of pencils}} = \frac{2}{10}$$

The *Product Rule* is now stated by example:

$$P(R, H) = P(R) \times P(H|R) = \frac{3}{10} \times \frac{2}{3} = \frac{2}{10}$$

$$= P(H) \times P(R|H) = \frac{6}{10} \times \frac{2}{6} = \frac{2}{10}$$

= probability a random choice is hard *and* red.

If 2 random variables, e.g., X and Y, are statistically independent, then $P(X) = P(X|Y)$ and it follows, $P(Y) = P(Y|X)$. In this case, the product rule may be written: $P(X,Y) \equiv P(Y,X) = P(Y) \times P(X)$.

In this example, the ten pencils collectively are known as the parent population. The one pencil randomly selected is the sample of size $n = 1$. The manner in which the sample is selected is of major importance. If the mathematics are to be valid, nothing one does, objectively or subjectively, must prejudice the data.

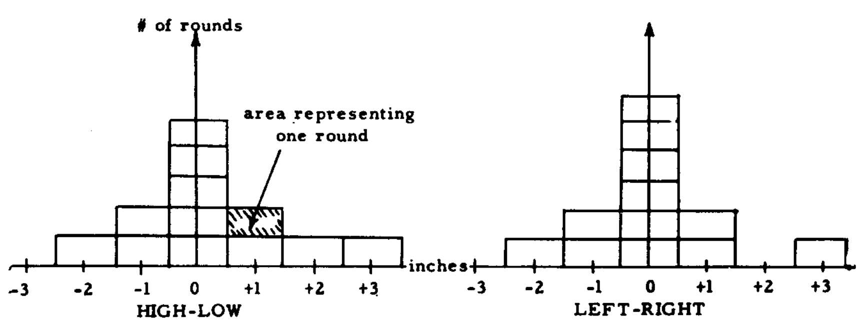
6-6.3 STATISTICS

To analyze a set of data in an effort to discover trends or predict performance, one tries to answer the following questions: (1) "Where is the center of the distribution, or what is a representative single-number description of the data?" (2) "What is the dispersion, variation, or spread?" (3) "Is the distribution skewed or symmetric?" This text considers the answers to (1) and (2) only, and infers probabilities from the answers.

There are several ways of answering the questions posed in (1) above; e.g., mean (average), mode or median. The most useful of these, the mean or average, is centroidal, i.e., is located at the balance point of the data. For a symmetrical frequency distribution, mean, mode, and median are essentially the same. Imagine an experiment in which a number of rifle rounds are fired over a fixed range at a single target point. Measure, to the nearest inch, the horizontal and vertical distances from the center of bull's eye to the actual strike point of each round and tabulate these data as follows:

Round No.	High or Low (High is +)	Left or Right (Right is +)
1	+1	0
2	−2	+1
3	+2	0
4	0	0
5	−1	−2
6	0	+1
7	0	0
8	−1	−1
9	+1	−1
10	0	0
11	+3	+3
12	0	0

These data may be graphed as histograms:



Note that, implied in measuring to the nearest inch, is the fact that the measurement "0" really means within — 0.5 in. to + 0.5 in.

It is apparent that, if the average miss is not 0, there is an aiming error, therefore it is useful to compute the averages for the data presented. Let the individual data be denoted by x with a subscript. Then the mean or average is given by:

$$\bar{x} = \frac{x_1 + x_2 + \ldots + x_{12}}{12} \equiv \frac{1}{12}\sum_{i=1}^{12} x_i \qquad (6\text{-}1)$$

Thus, $\bar{x}_{H-L} = \frac{3}{12} = .25$ inches high, is the average miss high or low, and $\bar{x}_{L-R} = \frac{1}{12}$ inches right, is the average miss left or right. Therefore, based on these scant data, one can say that there is apparently no aiming error because both x's are within — 0.5 to + 0.5 inches.

If asked "What is the probability of being within ½ inch of a horizontal line through the center of the bull?" one might answer, "From the first histogram, 5 of the 12 rounds fired fell within ½ inch. Based on these scant data, P (vertical error $< .5$ in.) $= 5/12$ in. Further, one might infer that essentially all rounds will fall within 3.5 in. since 12 out of 12 in our sample fell within 3.5 in. of the horizontal center line."

The area of each histogram is 12 rounds. Dividing the ordinates by 12, in effect, divides the area by 12 making it equal one. In short, the graph has been normalized, i.e., the total area has been made to equal one. This normalization changes the frequency distribution (histogram) to a probability distribution in which the area between two values of miss distance equals the probability that any given round will fall within those two values.

There are obvious weaknesses in the technique employed thus far. First, measurements to the nearest inch are not very precise. Further, a sample size of 12 is not large enough. Therefore, imagine firing a very large number of rounds (say ∞) measuring each miss distance precisely. In this case, the histograms will smooth out into continuous, rather than stepped, curves. The sum of a large number of independent random quantities practically always satisfies the normal law, i.e., approximates extremely well to a function of the form e^{-x^2}.

The normal frequency function is given by

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left(\frac{x-m}{\sigma}\right)^2}$$

where m is the true mean or average of the population, and σ is the true standard deviation of the population.

S ≡ standard deviation of the sample

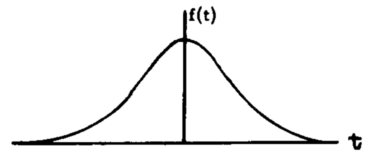
≡ root-mean-squared deviation

$= \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2}$ is a biased estimate of σ,

but $S \simeq \sigma$ when the sample size n is large.

By employing the standardized variable, $t = \frac{x - m}{\sigma}$, the normal frequency distribution becomes:

$$f(t) = \frac{1}{\sqrt{2\pi}} e^{-t^2/2}$$



The following properties of the normal curve are easily verified:

(a) Maximum ordinate occurs at $t = 0$ (or $x = m$).

(b) Curve is symmetrical about $t = 0$ (or $x = m$).

(c) The "tails" of the curve rapidly approach the horizontal axis.

(d) There are two inflection points at $t = \pm 1$ (or at $x = m \pm \sigma$).

(e) Total area under $f(t)$ is 1, i.e.,

$$\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e^{-t^2/2}\, dt = 1.$$

(f) The probability of a random value of t lying between A and B equals the area under $f(t)$ between A and B, i.e.,

$$P(A \leq t \leq B) = \int_A^B f(t)dt$$

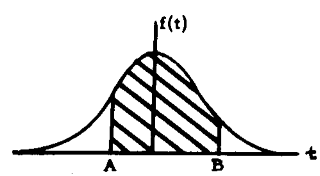


Table 6-1 gives values of $\int_{-\infty}^{t} f(t)dt$ for several values of t. By use of this table, $P(A \leq t \leq B)$ can be found.

Further, if it is desired to know what values of t would delimit some fractional part of all events this too can be determined from the table.

It is important to recall that the parameters m and σ, essential to the use of probability tables, are population values. These must be approximated from experimental or sample data. The best estimate of m is the average of the sample data, $\bar{x}$. However, the best estimate of σ is given by

$$\sigma \simeq \sqrt{\frac{n}{n-1}}\,S = \sqrt{\frac{n}{n-1}}\sqrt{\frac{1}{n}\sum_{1}^{n}(x_i-\bar{x})^2}$$

$$\simeq \sqrt{\frac{\sum (x_i-\bar{x})^2}{n-1}}$$

It is enlightening to note from Table 6-1 that a normally distributed random variable will fall within 1σ of the mean $[1 - 2\,(.1587)] \cdot 100\%$ of the time, or 68.26% of the time. Areas, or probabilities can be summarized as follows:

Interval	Area or Probability
$t = -1$ to $+1$ or $x = \bar{x} - \sigma$ to $\bar{x} + \sigma$	.6826
$t = -2$ to $+2$ or $x = \bar{x} - 2\sigma$ to $\bar{x} + 2\sigma$	.9545
$t = -3$ to $+3$ or $x = \bar{x} - 3\sigma$ to $\bar{x} + 3\sigma$	.9973

Mortars, bombs, rockets, and guided missiles, i.e., missiles approaching the target plane from a nearly vertical direction, present very nearly circular dispersion patterns. It is therefore convenient to define a circular error probable *CEP* which gives that value of miss distance within which 50% of the rounds or missiles will fall. It may be seen from Table 6-1 that $+t = .6745$, gives the limits of the centrally located half of

TABLE 6-1 AREAS UNDER NORMAL CURVE FROM $-\infty$ TO $t = \frac{x - m}{\sigma}$)

$t=\frac{x-m}{\sigma}$	$\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{t} e^{-t^2/2}dt$	$t=\frac{x-m}{\sigma}$	$\int_{-\infty}^{t}$
−3.5	.0002	−1.5	.0668
−3.4	.0003	−1.4	.0808
−3.3	.0005	−1.3	.0968
−3.2	.0007	−1.2	.1151
−3.1	.0010	−1.1	.1357
−3.0	.0013	−1.0	.1587
−2.9	.0019	− .9	.1841
−2.8	.0026	− .8	.2119
−2.7	.0035	− .7	.2420
−2.6	.0047	− .6	.2743
−2.5	.0062	− .5	.3085
−2.4	.0082	− .4	.3446
−2.3	.0107	− .3	.3821
−2.2	.0139	− .2	.4207
−2.1	.0179	− .1	.4602
−2.0	.0228	0.0	.5000
−1.9	.0287	+ .1	$=1-\int_{-\infty}^{-.1}$
−1.8	.0359	+ .2	
−1.7	.0446	+ .3	$=1-\int_{-\infty}^{-.3}$
−1.6	.0548	+ .4	
−1.5	.0668	+ .5	$=1-\int_{-\infty}^{-.5}$

Note:

Only integrals for negative values of t are given; by symmetry and the fact that $\int_{-\infty}^{\infty} f(t)dt = 1$, we have

$$\int_{-\infty}^{+t_0} = 1 - \int_{-\infty}^{-t_0}$$

t values. If it is assumed there are no aiming errors (i.e., $m = 0$) then

$$t = .6745 = \frac{X_{50} - 0}{\sigma}$$

or

$$X_{50} = .6745\sigma_x = \text{probable error of } X.$$

Similarly,

$$Y_{50} = .6745\sigma_y = PE_y$$

$$\sigma_x = \sigma_y = \sigma$$

(Since, a circular dispersion pattern is hypothesized.)

It is shown in more advanced texts that

$$1\ CEP \doteq 1.1774\sigma$$

A knowledge of statistical analysis of errors (in terms of standard deviation and probable error) is helpful because the performance of weapon system components (e.g., CEP, range and deflection probable error, fuzing error, etc.) is expressed in such terms. Actual data for specific systems are classified and presented only in classroom discussions.

6-7 PROBABILITY OF A SUCCESSFUL MISSION

The knowledge that a single round will succeed in its mission is influenced by a considerable chain of circumstances. Consider, by way of illustration, a flat trajectory weapon with a deflection standard deviation of 1 mil, firing on a target 6 yards wide, at a range of 1000 yards. If the weapon is properly aimed at the center of the target, an allowable error of 3 standard deviations exists. This is sufficient allowance to practically insure a hit, since it has been shown that a probability of .9973 exists for limits of $\pm 3\sigma$. This example has been over-simplified. In reality, .9973 is the probability of a hit on the hypothesis (or condition) that the aim is correct; thus, the probability of a given weapon hitting a target is dependent on the aim. Aim is clearly a function of crew training, crew eyesight, and proper functioning of the fire control equipment.

Consider the same system manned by a perfect crew with the further condition that the projectile is a high explosive shell. The probability of killing the target is the joint probability of proper functioning of the high explosive train on the hypothesis of a hit. Thus, by the *Product Rule,* the P (kill) $= P$ (hit) $\times$ P (proper functioning of high explosive train).

The problem can be further compounded by introducing the probabilities of proper performance of each link in the chain of events which precedes a kill. Included in the chain would be a factor for the hardness or softness of the target, i.e., the probability of a definite kill for one round. The latter involves the appropriateness of attacking the given target with the given terminal ballistic effect. Hence, the net kill probability might take the form

$$\begin{aligned} P(\text{kill}) = {} & P\ (\text{proper mechanical functioning}) \\ & \times P\ (\text{proper crew performance}) \\ & \times P\ (\text{hit on the hypothesis of proper aim}) \\ & \times P\ (\text{kill on the hypothesis of a hit}). \end{aligned}$$

Fortunately, most of these probabilities are, or with sufficiently energetic training and discipline may be made, high. The two dominant factors are obviously the size of the target and the accuracy of the delivery system, both expressed in terms of probable error or standard deviation.

6-8 DAMAGE DISTRIBUTION FOR LARGE YIELD WEAPONS

When an atomic weapon is detonated over a given target it may be expected, except for unduly high bursts, that there will be a zone (extending radially from ground zero) in which there will be almost certain damage to the target. It may also be expected that, outside of the certain damage zone, there will be a zone of probable damage in which the actual damage imposed will vary with distance from ground zero from virtually complete damage to virtually no damage. Similarly, outside of the zone of probable damage, there will be a zone of no damage. The lines of demarcation between these zones will not be capable of precise definition. However, these zones will usually exist. It is possible to determine the distance from ground zero at which

the probability of damage is that desired or required. In doing this it is convenient to work with that distance at which the probability of damage is about 0.5.

Three damage levels, light, moderate, and severe, used to describe the degree of damage tactically important are defined as follows:

(a) Light. Superficial, can still perform mission.

(b) Moderate. Out of action for present engagement but can be repaired.

(c) Severe. Permanently out of action.

The required damage levels are moderate and severe.

The damage radius (R_D) is that radius (from ground zero) within which as many target elements escape the specified damage as sustain it outside. $R_D \simeq R_{50}$ where R_{50} is the radius at which the probability is .50 that a target element will sustain the specified damage.

6-9 THE DAMAGE FUNCTION

The relationship between probability of damage and distance from ground zero as it exists for a given set of conditions, is known as the damage function applicable to that set of conditions. As conditions vary, e.g., different targets, different effects, different burst conditions, it may be expected that the curve representing the damage function will change. These changes will evidence themselves in the slope of the damage curve and in the magnitude of R_D. Consequently, the relative size of the zones of certain damage and of probable damage change. The slope of the curve is related to a variability factor. The proper variability depends upon the variation in target response expected from the type of effect being utilized.

The plot in Figure 6-3 shows three curves of a family of curves, each of which corresponds to different target responsiveness. The curve for the target, shown by a solid line, is annotated with zones of damage and radius of damage R_D. The least variable target, shown by a dotted line, is more discriminating, i.e., the zones of damage are more sharply delimited. The most variable target has an extensive zone of probable damage.

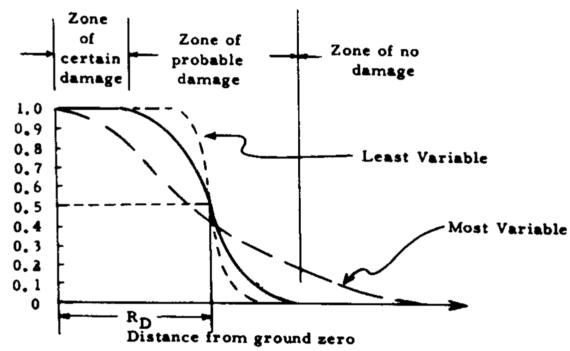


Fig. 6-3 Damage functions for two different sets of conditions.

6-10 FACTORS REGULATING OVERALL SYSTEM ERRORS

Most delivery systems are subject to delivery errors which, in some cases, are quite large. The probable delivery error must, therefore, be taken into account in determining the probable variation of the actual ground zero from the planned, or desired, ground zero. This is important in planning the utilization of weapons as it may greatly affect the amount of damage to the target.

6-10.1 GENERAL

The selection of the weapons system, a weapon, and its delivery means, is vital to the success of a planned atomic strike. The procedure used in selecting the weapons system is referred to as a target analysis. The atomic weapons staff officer performs the target analysis in order to present to the commander, recommendations on weapon systems to use and the details of their employment.

6-10.2 FACTORS CONSIDERED

There are many factors that need to be considered in the selection of a weapons system. Generally, they can be broken down into the two

categories of technical and tactical factors. Under any given situation certain of the factors may assume greater importance than others thereby exerting a greater influence on the choice of a particular weapons system.

(a) *Mission or objective of the attack.* The most important factor in weapon selection is the objective of the attack. Other factors may have an important bearing which will require some modification in final weapons systems selection but, unless the objective of the attack is met, the attack will not be successful. The results desired from the attack are determined and clearly stated by the commander. Many considerations including the mission, type of maneuver, target nature and vulnerability, and strength and disposition of opposing forces, will influence the commander's decision as to the type and amount of damage needed against the entire target or any elements thereof. In arriving at the stated objective the commander is assisted by his staff.

(b) Troop safety or other command limitations. The second factor, troop safety or other command limitations, also plays an important part in the selection of a weapons system. The tactical disposition of friendly troops and the protection from the effects of atomic weapons available to them must be considered in relation to the size of the atomic weapon and the accuracy of the delivery means available. In areas occupied by civilians, humanitarian consideration may make it desirable to avoid or minimize civilian casualties or material damage in certain areas. Minimizing damage to installations such as bridges, communication centers, and other facilities which may be of future value to friendly operations, may also be specified by command limitations. The avoidance of obstacles, either by radioactive contamination or from rubble may be another limitation of the objective of the atomic attack. The commander may well specify any of the above as limitations or results not desired from the atomic attack; this, in turn, may modify the final selection of a weapons system.

(c) Weapon availability (logistics). Weapon availability affects the final selection not only from the viewpoint of actual weapon availability but also from the viewpoint of the characteristics of the weapons.

(d) Delivery system capabilities. Various delivery systems have different characteristics. Some of the systems are inherently more accurate than others. This factor may govern in some cases where troop safety assurances cannot otherwise be met. The air delivery system is inherently flexible, yet, because of possible enemy countermeasures, weather, or navigational problems, the selection of such a delivery system may be unsound. Additionally, the problems of control and coordination make it desirable that the delivery means be under the control of the army commander. The gun delivery system is accurate in delivery, and not affected by weather or subject to interception, but is limited in use by its range capabilities. Each system available in any particular situation must be judged in the light of the objective of the atomic attack.

(e) Weapon characteristics. The characteristics of the weapons will also affect the final choice in some situations. For example, a certain weapon may be the only one that has an underground burst capability whereas another weapon may be the only one capable of being prepositioned.

(f) Economy. The third technical factor that must be considered is economy. The smallest weapon which will achieve the desired results, all other factors being equal, should be chosen for reasons of economy. As an example, an attack is being considered on troops in forests, and it has been determined that a casualty radius of 1300 yards is needed. Atomic weapons should be considered which will give the required casualty radius. All other factors being equal the smallest yield weapon with the required casualty radius should be selected.

6-10.3 POINT TARGETS

A point target may be a single element such as a building or a bridge, or it may be a small area target. The term small is a relative term. A target is small only by comparison with the radius of damage (R_D). Thus, a very hard target (one requiring high effect values) of 200 yards radius is not a small target when attacked with a weapon of R_D of 400 yards. A target of $R_D = 200$ yards is small when compared with an R_D of 1500 yards. The assumption that an area target can be treated as a point target is based on judgment and the requirement for accuracy.

Problems involving the probability of damage to point targets are solved by means of the basic point target chart, Figure 6-4, or the point target

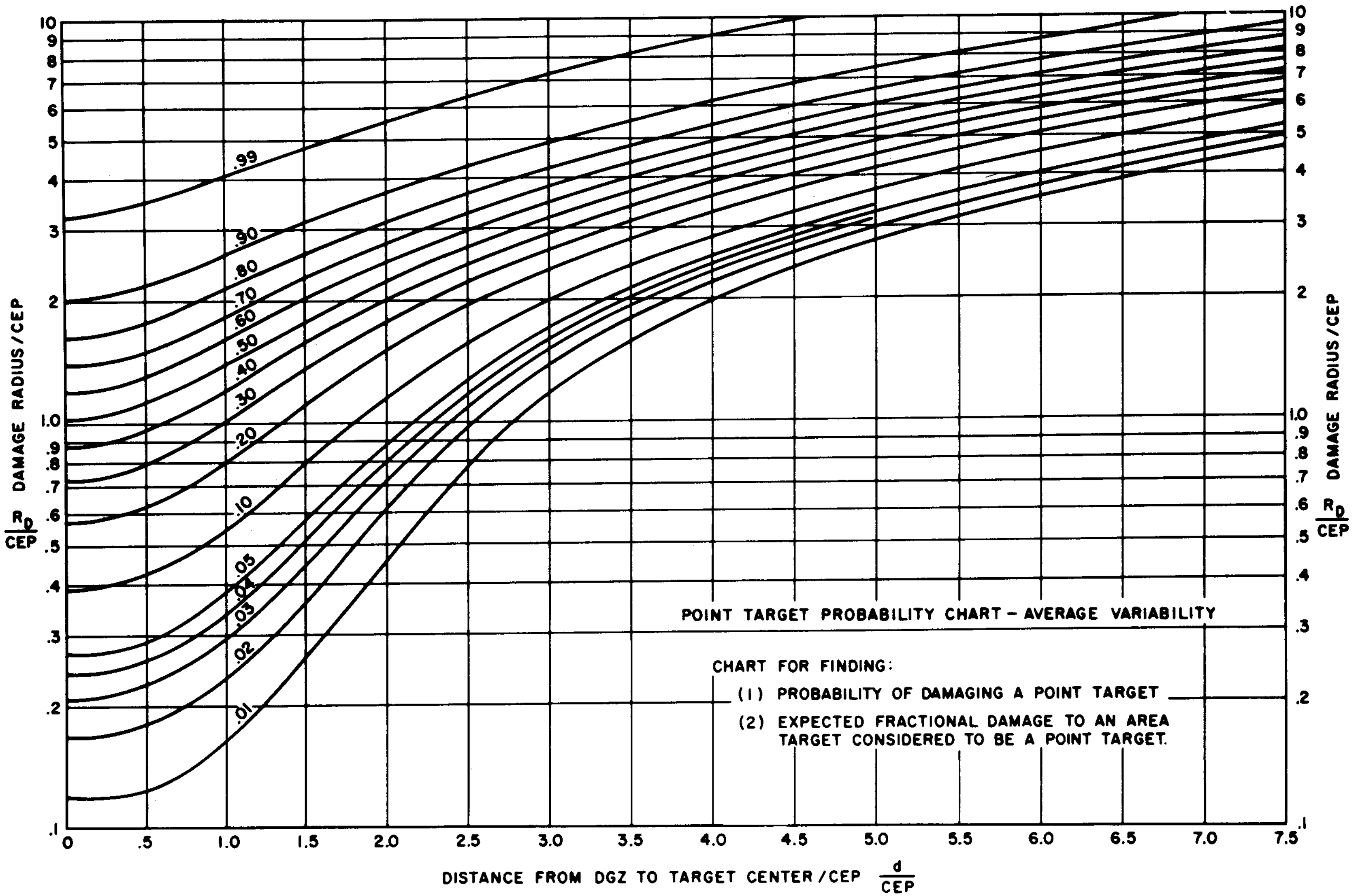


Fig. 6-4 Point target chart, average variability.

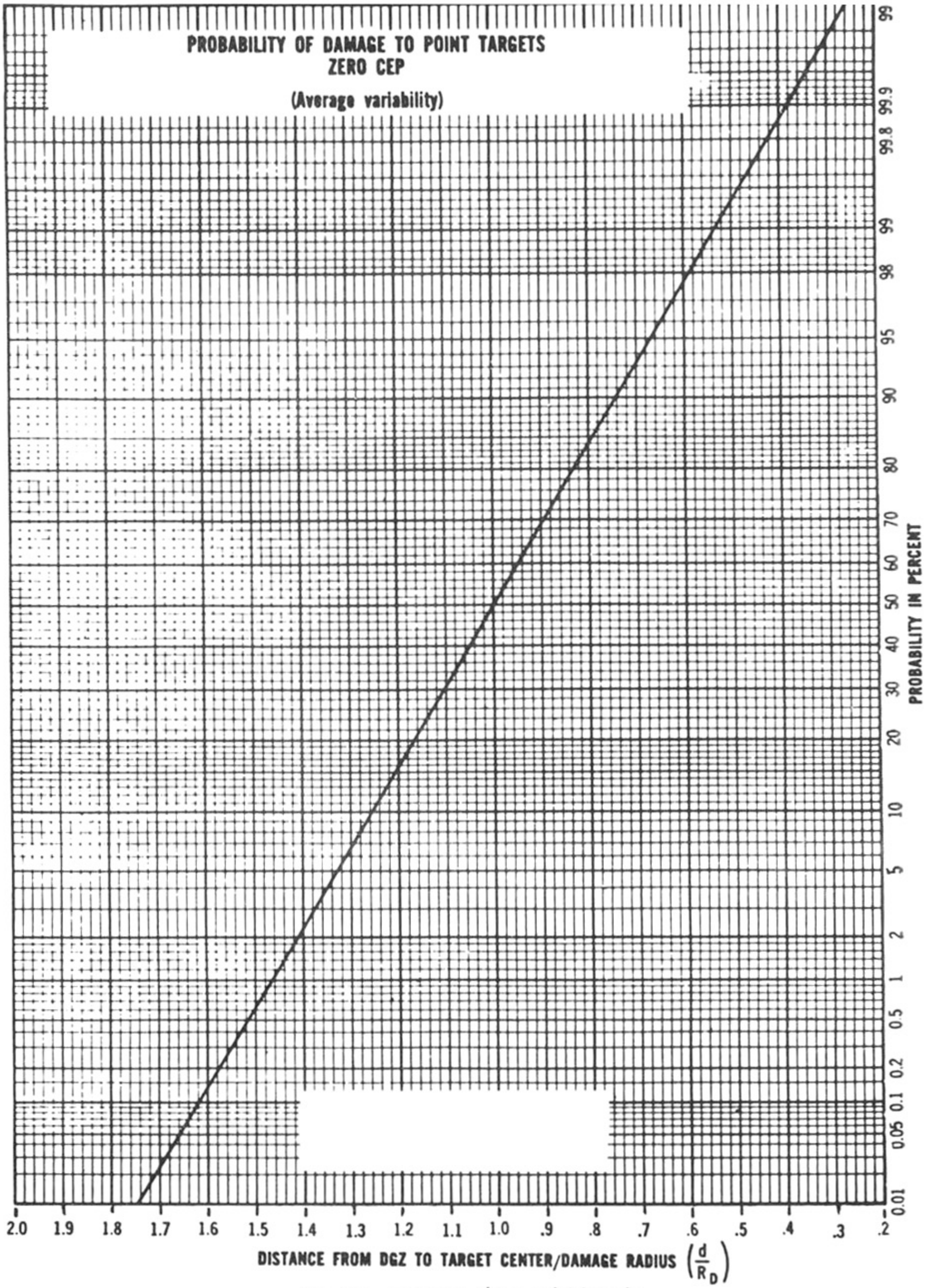


Fig. 6-5 Extension chart, point targets.

extension chart (Figure 6-5). The basic point target chart, Figure 6-4, provides means for finding the probability of damaging a point target, or a small area assumed to be a point, when the delivery error (*CEP*), damage radius (R_D), and distance (d) from *DGZ* are known. The extension chart, Figure 6-5 is used whenever values are off the basic point target charts, and it must be used when there is no delivery error. The probability contours of the point target chart give directly the probability of damage to a target considered as a point. If the target is a single element, the probability (P) of damage represents the assurance that the element will sustain severe or moderate damage depending on the criteria used. Where a small area target consisting of several elements is considered a point target, the probability (P) of damage to the point may also be construed as the average fractional damage which would occur if the attack were repeated a large number of times under identical conditions. As an example, if the probability of causing casualties to an infantry company (considered as a point target) were determined to be 60%, and if it were estimated that 150 troops were in the company area, then, on the average, 90 of them would be casualties.

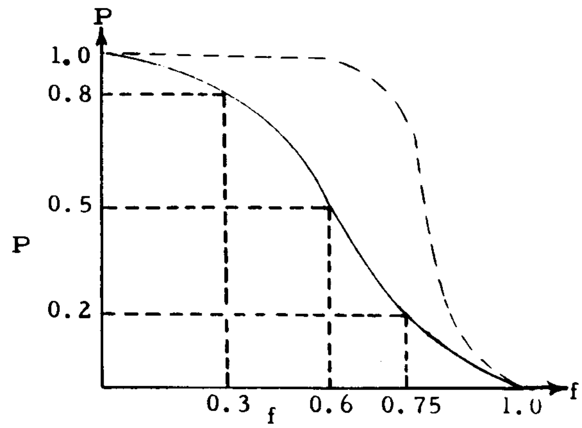


Fig. 6-6 Two typical P(f) curves. The dotted curve indicates the P(f) curve for the larger yield weapon (hence, the larger R_D).

6-10.4 AREA TARGET CONSIDERATIONS

The determination of damage occuring to (or being imposed on) an area target is more complex than for a point target. In the case of the point target, since the target either will or will not be damaged, there are but two pertinent probabilities; the probability of damage and the probability of no damage. In the case of area targets however, the target may be totally damaged, partially damaged, or not damaged. There is a probability associated with every degree of partial damage to the target as a whole, as well as a probability of complete damage and a probability of no damage.

Since atomic weapon effects are evidenced spherically about the point of detonation, they are evidenced circularly on the ground about ground zero. Consequently, target shape is important. For simplicity, area target considerations are limited to circular targets.

It is reasonable to expect that the probability of at least 10% damage to a target will be greater than the probability of at least 90% damage, under the same conditions. The degree of partial damage to the target as a whole (i.e., to all target elements) is called fractional damage. Hence, generalizing the foregoing statement: the probability of a large fractional damage will be less than the probability of a small fractonal damage. This relationship can be illustrated by what is called the *P(f)* curve for the circumstances at issue (P referring to probability of damage; and f referring to fractional damage). Fractional damage is not to be interpreted with respect to all target elements. A typical *P(f)* curve is illustrated in Figure 6-6, which illustrates the following relationships between probability (P) and fractional damage (f):

P	f
0.80	0.30
0.50	0.60
0.20	0.75

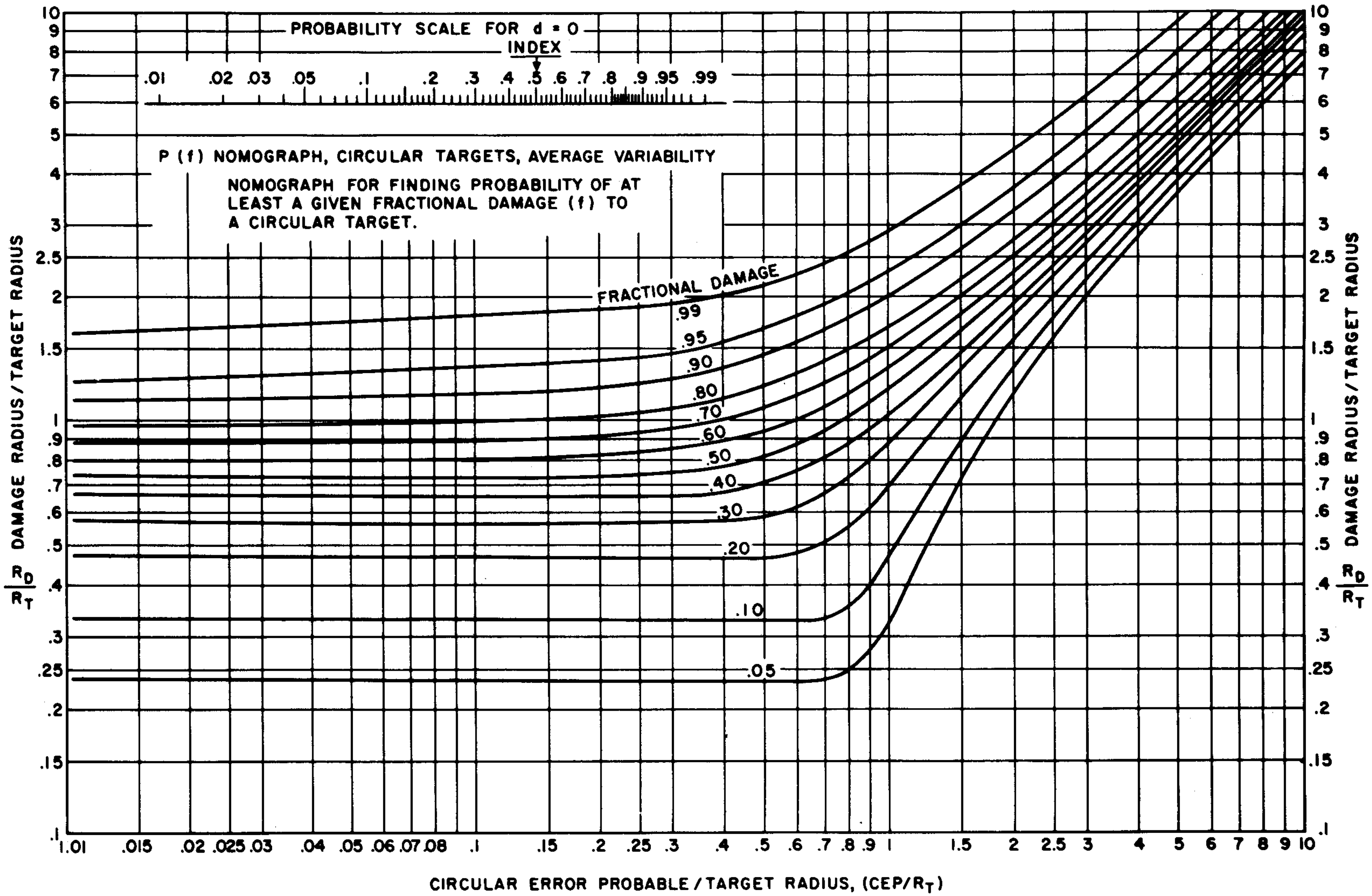


Fig. 6-7 P(f) nomograph, average variability.

6-11 THE *P(f)* RELATIONSHIP FOR CIRCULAR TARGETS, NON-ZERO *CEP*

Figure 6-7 has been designed to enable determination of the *P(f)* relationship for circular targets of radius R_T when attacked with a weapon of damage radius R_D, delivered with a circular probable error (*CEP*), provided the desired ground zero (*DGZ*) coincided with the target center. Often one is not concerned with the entire *P(f)* curve but rather with a specific point on it. For example: it has been decided to impose a 40% fractional damage on a designated target and that there be a 90% assurance (probability) of attaining at least that damage. This nomograph, together with the probability scale associated therewith, enables determination of the required R_D to comply with the commander's desires, provided the *DGZ* is the target center.

6-12 IRREGULAR TARGETS

(a) Targets which are not generally circular in shape may be considered as follows:

1. Rectangular targets. Targets roughly rectangular in shape with the long side less than two times the short side can be reduced to an equivalent circular area without serious error. In using the charts and nomograph, R_T should be equated to the radius of the circle of equivalent area. If the sides of the rectangle are X and Y, then,

$$R_T = \left(\frac{XY}{\pi}\right)^{1/2} = 0.564\sqrt{XY}$$

2. Elliptical targets. If the long axis is less than twice the short axis, the area may be equated to that of a circle with no serious error. ($R_T = \frac{1}{2}\sqrt{ab}$, where a and b are the lengths of the major and minor axes, respectively.) The area may also be found by approximation, by planimetering, or by counting grid squares.

(b) Irregular targets which are not amenable to reduction to a circular target of equivalent area must be considered as a system of points. Targets such as marching troops or armored columns, or other very linear or irregular targets, can only be solved by considering a series of points within the area of concern and determining the average probability of damage. The greater the number of points considered, time permitting, the more accurate the determination of damage will be. The damage determined will be that which can be expected on the average.

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CHAPTER 7

FRAGMENTATION

7-1 INTRODUCTION

When a charge of high explosive detonates inside a closed metal container, the container is blown into fragments. These are hurled outwards at high velocities and in effect become projectiles with a capacity for inflicting damage upon nearby objects. Capacity for damage depends upon fragment size, velocity, and distribution. A container which erupts into dustlike particles or into a few very large pieces is of little value. Knowledge of the fragmentation process is therefore basic to the design of many types of missiles. Terminal ballistic studies attempt to determine the laws and conditions governing the speed and distribution of fragments; the sizes and shapes that result from the bursting of different types of containers; and the influence of the bursting charge fragmentation.

7-2 NATURE OF THE FRAGMENTATION PROCESS

Upon detonation of the high explosive in a missile, the metal case expands very rapidly because of the internal pressure of the expanding products of the detonation.

Flash radiographs of a tetryl loaded 20-mm shell, detonated statically, illustrate the phenomenon of fragmentation as it occurs in artillery shell. There are nine pictures (Figures 7-1, (a) to (i) incl.). Figure 7-1(a), the reference picture, shows the shell before detonation. Exposure time is approximately one microsecond (1/1,000,000 of a second).

7-3 BALLISTICS OF FRAGMENTS

Fragmentation is not the only result of detonation of explosive missiles, since only forty percent of the gas energy normally is absorbed in the fragmentation process. The balance of the available energy is consumed in the creation of a compressive wave in the air surrounding the projectile. The fragments resulting from detonation of a missile are propelled at high velocity, and within a very short distance from the center of explosion, pass through the shock wave which is retarded to a greater extent by the air. The velocity of the shock wave in air is dependent upon peak pressure in the shock wave front and the pressure, temperature, and composition of the undisturbed air. Its velocity is reduced according to the square of the distances from the center of explosion until, at a considerable distance, the velocity becomes equal to that of sound in air.

It is apparent that it is difficult to obtain ballistic data on individual fragments; nor is it necessary. Statistical analysis of the fragmentation of the whole container provides essential practical data. The ideal fragmentation missile is one which would break up into uniform fragments with a size and velocity fulfilling predetermined tactical requirements. This ideal has not yet been attained, but the size and shape of fragments can be controlled to a limited extent. The problem of determining optimum fragments illustrates the need for fragment flight characteristic (drag) as well as the vulnerability of the prospective target in terms of fragment mass and striking velocity.

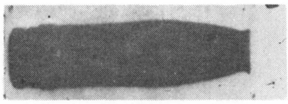

Fig. 7-1(a) Shell before detonation.

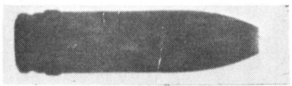

Fig. 7-1(b) Shell two microseconds after initiation of the bursting charge.

Fig. 7-1(c) Five microseconds after initiation showing the shell case in the process of swelling.

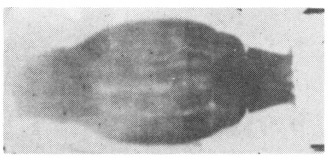

Fig. 7-1(d) Eleven microseconds after initiation cracks can be seen in the shell case which has expanded to almost twice its original girth.

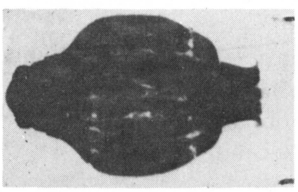

Fig. 7-1(e) Twenty microseconds after initiation showing continued lateral movement of the shell case fragments. The expanding gases are escaping through the failure cracks.

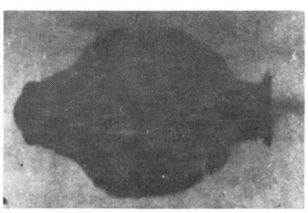

Fig. 7-1(f) Thirty-four microseconds after initiation showing continued growth of fragmentation perpendicular to the longitudinal axis of the projectile.

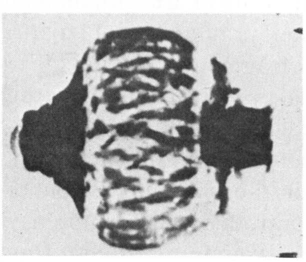

Fig. 7-1(g) Thirty-nine microseconds after initiation.

Fig. 7-1 Detonation of a 20-mm shell. (Sheet 1 of 2)

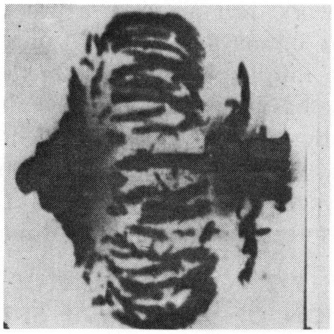

Fig. 7-1(h) Fifty-four microseconds after initiation showing the extent to which the fragments fly off in the direction perpendicular to the surface of the casing. The disc shaped ***side spray*** *which exceeds the* ***nose*** *and* ***tail spray*** *in intensity of fragmentation is the main instrument of damage in most missiles.*

Fig. 7-1(i) Ninety-two microseconds after initiation showing the wide variance in size and shape of fragments. All the fragments have by now received their initial velocities.

Fig. 7-1 Detonation of a 20-mm shell. (Sheet 2 of 2)

7-4 INITIAL VELOCITIES OF FRAGMENTS

The initial velocity of a fragment depends mainly on:

(a) The C/M ratio where C is the mass of explosive per unit length of projectile and M is the mass of metal per unit length of projectile.

(b) The characteristics of the explosive filler (brisance, power).

Table 7-1 illustrates the relationship between C/M ratio and initial velocities (V_0) determined from a series of tests using cylinders of an internal diameter of 2 inches and uniform wall thicknesses as indicated. The explosive filler used was TNT.

TABLE 7-1 FRAGMENT VELOCITIES FROM VARYING CONTAINER WALL THICKNESSES

Wall Thickness	Inches				
	½	⅜	5/16	3/16	⅛
C/M	.165	.231	.286	.500	.775
V_0 (ft/sec)	2870	3240	3800	5100	6100

Initial fragment velocities can be estimated experimentally by measuring fragment penetration into a material such as soft pine or celotex, and adjusting estimated velocity in terms of fragment mass, shape, and drag coefficient. Semi-empiricallv, the approximate initial velocities are,

$$V = K\sqrt{\frac{C}{M + C/2}} = K\sqrt{\frac{C/M}{1 + 1/2\, C/M}}$$

where

V = initial fragment velocity, ft/sec

K = constant associated with the power and brisance of the explosive used

C and M, as defined above

The primary reason for the relatively low velocities of fragments from the container with the greatest wall thickness, is that a large part of the energy released by explosion is absorbed in rupturing the cylinder. However, the table could be changed considerably either by the use of different explosives, particularly those whose power and brisance differ, or by different wall material such as cast iron versus forged steel. Explosive power is usually considered as ability to do work over an area, a property more dependent on oxygen balance and after-burning than on rate of detonation. On the other hand, brisance has been defined as the ability to create destruction in the immediate vicinity of the explosion, which quality appears to be determined by the speed of establishment and the magnitude of pressure in the detonation wave.

TABLE 7-2 COMPARISON OF FRAGMENTATION OF 90-MM M71 SHELL USING TNT AND COMPOSITION B

	TNT Loading	Composition B Loading
Fragments (Pit Fragmentation Tests)	700	998
Fragment Velocity (Panel Penetration Tests)	2367 ft/sec	3231 ft/sec
Perforation in Steel Plates (at equal radii)	120	164

The best way then to achieve high initial velocities of fragments is to have a high C/M ratio, usually obtained in practice by the use of a thin walled container. This is not always possible however, since in many cases projectiles must be designed with thick walls to withstand setback forces or they may be purposely designed to give larger fragments. In these cases a more powerful explosive is needed having a higher brisance than that used in a thinner walled cylinder. Explosives containing RDX, for example, have both high brisance and good power. They are ideal then for producing high velocity fragments, although for certain applications they are too sensitive.

Velocities of fragments from an air burst have higher values than those obtained from detonation upon impact due to the velocity of the missile at the time of detonation. This fact is one of the reasons why VT or time fuzing provides more effective fragmentation effects.

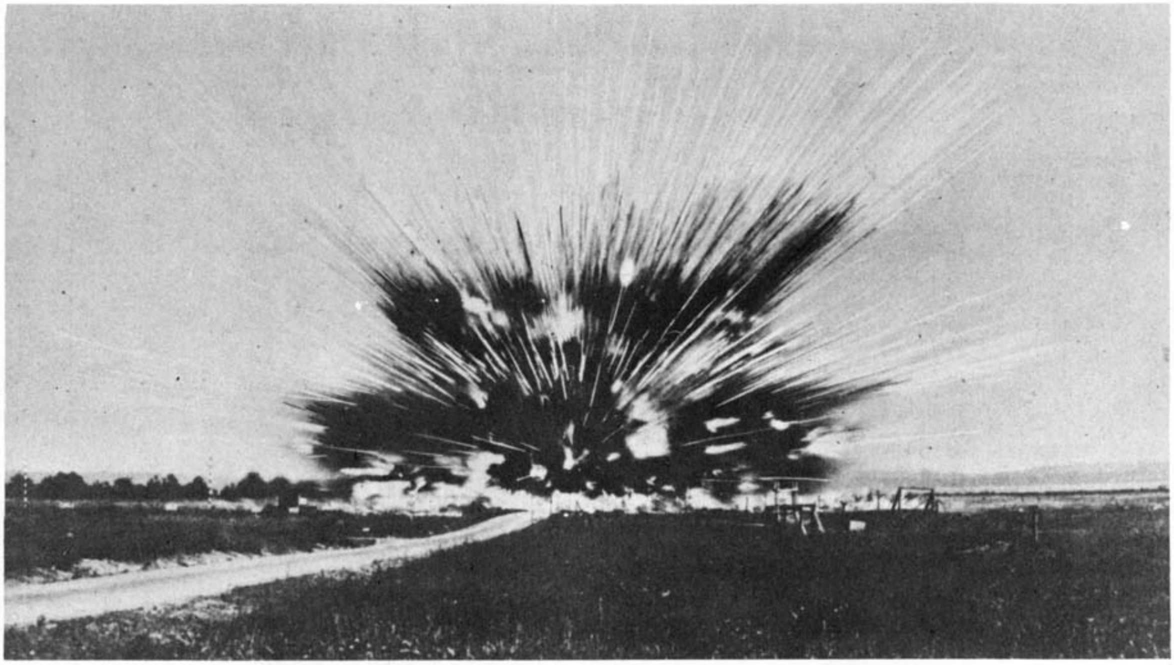

Fig. 7-2 Static nose-down detonation of a bomb.

7-5 DIRECTION OF FRAGMENT FLIGHT

The fragments from a missile usually fly in a direction perpendicular to the surface of the casing. For an artillery projectile, this can be readily seen by referring again to Figure 7-1 (i). Figure 7-2 shows the static detonation of a large bomb suspended nose down with nose about seven feet from the ground. The tracks of the fragments are made luminous by their heat. Note the black smoke, which represents the unoxidized solid products of the explosion, an indication of the incomplete oxidation of the explosive charge. The cone of tracks, opening upward in Figure 7-2, is called the 45° spray and originates from that section of the casing that connects the cylindrical part with the tail. The fragments almost parallel to the ground constitute the main side spray and originate from the cylindrical side walls of the bomb. The picture does not do full justice to the great density of fragments in the side spray. The slight upward deflection of the entire side spray is due to the fact that the bomb was detonated statically, nose down, and the detonation started from the bomb nose.

If either the bomb or shell had been detonated while in flight by VT fuze action, the side spray would have had a slight forward thrust; the resultant of the radial initial velocity of the fragments and the forward velocity of the bomb or shell.

7-6 NUMBER, TYPE, AND SIZE OF FRAGMENTS

The damage that will be produced by a fragment with a given velocity depends on the mass of the fragment. It is therefore necessary to know approximately for each missile the distribution of mass among all the fragments large enough to cause damage. Mass distribution of missile fragments is determined experimentally by means of static detonations in which the fragments, or a portion of them, are caught in sand pits. Usually, the side spray contains the most important part of the fragmentation. Such a spray will, in general, have a different mass distribution from

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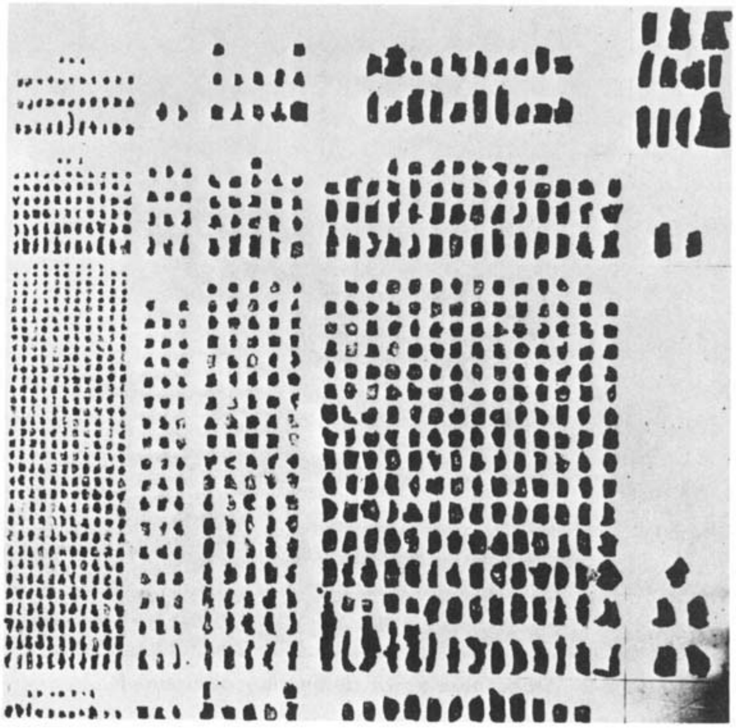

Fig. 7-3 Fragments from bomb, fragmentation, 220-lb, AN-M88.

that of fragments from the whole missile. In the static detonation of bombs, portions of the side spray, nose spray, or tail spray are collected in a sand pit. The fragments are separated from the sand by sifting through metal screens of four mesh to the inch. The fragments thus obtained, few of which have masses less than one gram, are then weighed and classified according to their masses into no more than six classes. Such sorting is shown in Figure 7-3 which represents recovery of fragments of an M88 220-lb fragmentation bomb loaded with Composition B.

In general, the shape of the fragments varies exceedingly. Many of them appear flat, their smallest dimension corresponding to the thickness of the swollen case, stretched by the expansion that follows detonation. Present fragmentation bombs have a light casing wrapped with a metal helix of square cross section in order to control to some extent the size, and therefore the distribution of mass among the fragments. When the bomb bursts, the helix is broken into pieces of comparatively uniform size as compared to the fragments of a general-purpose bomb. Fragments will vary from dust-like particles to relatively large pieces in GP bombs, where the size of fragments is not controlled.

While adjustment of the C/M ratio in shells can be used to change the degree of fragmentation of the shell wall, the size and number of fragments resulting from the shattered wall can also be adjusted by altering the material used in the wall. For example grey cast iron, an inherently brittle material, shatters into very small sand-sized pieces which have low killing power. Also they have little momentum and thus short range. This is unfortunate since the casting of shell bodies is desirable from a mobilization point of view.

A vital factor in the design of any ammunition item is its ability to be readily adaptable to quantity manufacture during mobilization or war. This country has a broad base of industry which could cast shell bodies. On the other hand, because forging is a widely used commercial

CHAPTER 8

BLAST EFFECTS BY CHEMICAL AND ATOMIC EXPLOSIONS

8-1 MECHANICS OF BLAST

When a conventional explosive charge or nuclear detonation occurs in air, expanding gases, often referred to as a flame front, burst forth and compress the surrounding air, thus initiating a shock wave. The gases themselves have little inertia, cool rapidly, and will have lost most of their velocity at a distance of 40 to 50 times the diameter of the charge. The belt of compressed air in the shock wave has initially a high outward velocity which it loses rapidly at first. The shock wave, except for its intensity, has all the characteristics of a sound wave, and travels through the surrounding air in the same manner; that is, without the transmitting medium moving along with it.

The shock wave is bounded by an extremely sharp front called the shock front which represents a discontinuity in density, pressure, and temperature of the medium through which it passes. Here the pressure rises abruptly from atmospheric to a peak pressure, then declines to atmospheric pressure. This phase is known as the positive or pressure phase of the shock wave. The pressure continues to decline to subatmospheric pressure and then returns to normal. The second phase is called the negative or suction phase. Figure 8-1 shows a typical pressure-time record of a blast wave at a particular distance from point of detonation. The negative phase of a shock wave is caused by the air and gases of detonation moving outward as a strong wind behind the shock front. They are prevented by their own inertia from slowing down quickly enough, as the pressure of the core of the gases subsides. The rarefication thus formed propagates outward, trailing the positive phase. After the positive phase passes, the wind reverses in direction and blows toward the point of detona-

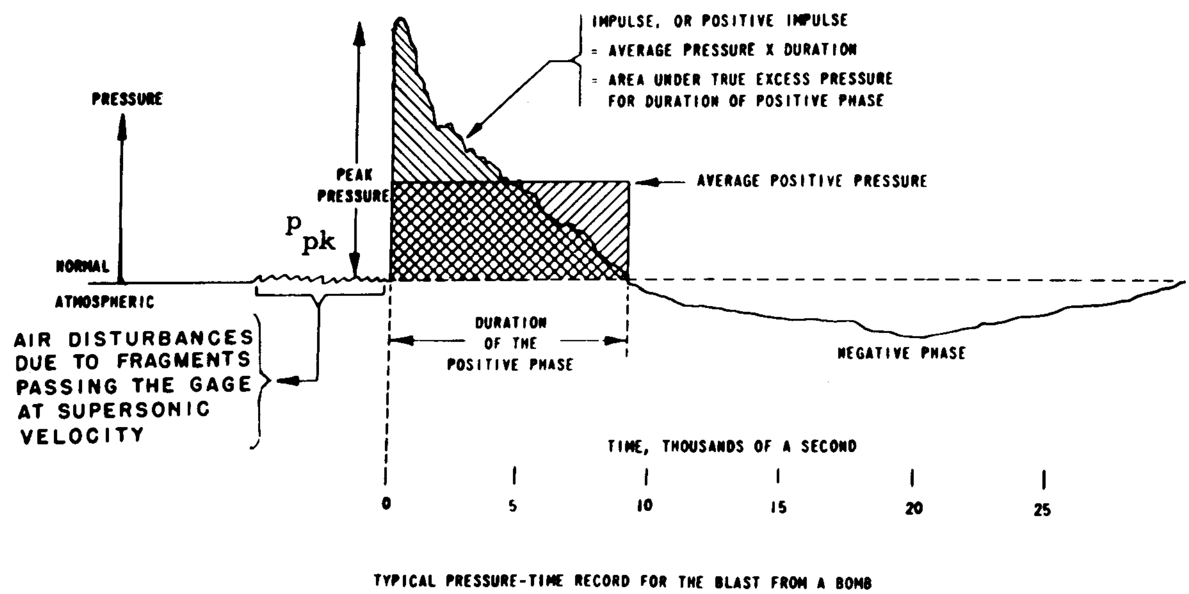

Fig. 8-1 Profile of a blast wave at a particular distance from point of detonation.

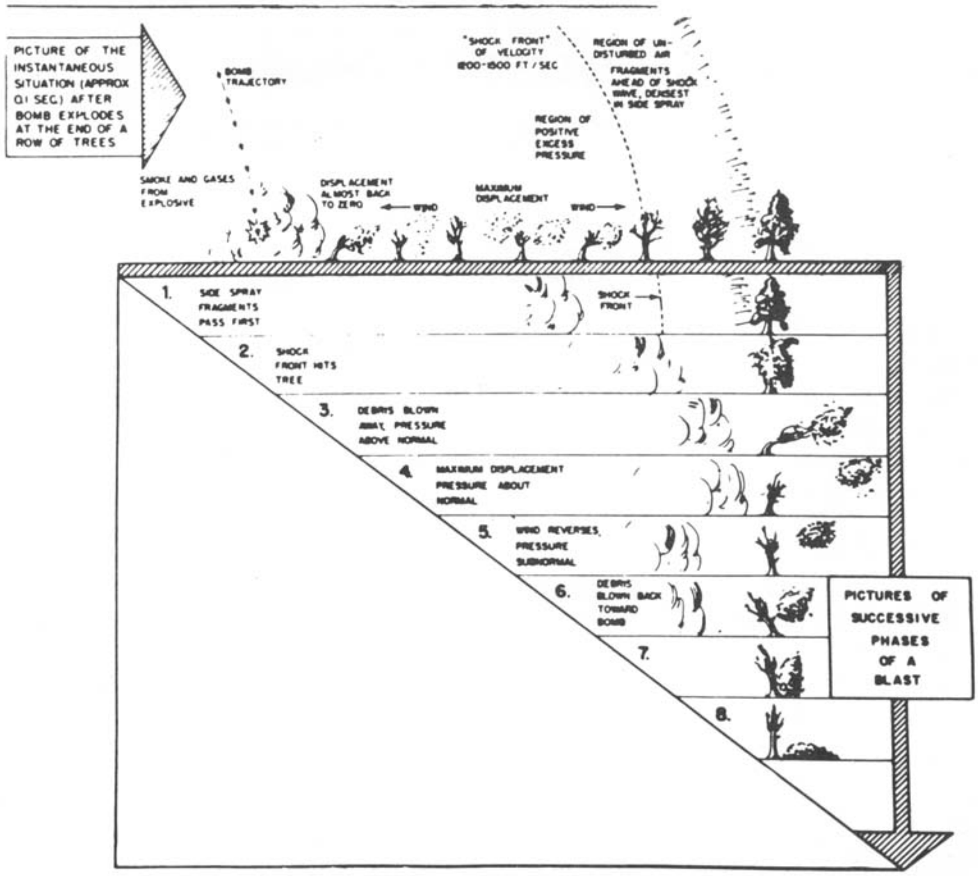

Fig. 8-2 Schematic representation of bomb explosion.

tion, gradually decreasing in velocity as the pressure returns to normal. Figure 8-2 shows the effect of this action on an object in the path of the shock wave.

An atomic detonation resembles a high explosive detonation in that the explosive effect is the result of the very rapid liberation of a large quantity of energy in a relatively small volume. But atomic detonations differ in three important aspects: first, the amount of energy is thousands of times as great as that produced by even the largest high explosive weapons; second, the energy released consists of blast, intense heat, light, and penetrating nuclear radiation; and third, under some burst conditions residual radioactivity may be produced which may be significant from a military and civil defense point of view. While the pressure-time relationships as depicted in Figure 8-1 are applicable to atomic detonation, the accompanying thermal effects may often initiate slight pressure rise near the target area immediately prior to the passage of the primary blast wave, and augment damaging effects. This wave, when present, is referred to as the precursor wave.

The blast from an explosion in air can be visualized as a sphere bounded by the shock front (probably less than a 1000th of an inch thick) beneath which is a layer of compressed air, the positive phase; and then a thicker layer of rarefied air, the negative phase. The core of the sphere is filled with air of normal atmospheric pressure except in the early stages. At first the sphere expands very rapidly, its radius increasing initially as much as 20,000 feet per second in some cases. Then it slows down, until

eventually the increase stabilizes at the speed of sound, 1100 feet per second at 60°F. As the sphere increases in size, the two layers under the shock front gradually increase in thickness but decrease in pressure difference until they finally degenerate into sound waves. Because of the shape of the charge and the manner in which the explosion is initiated, the blast wave may not spread out from the explosion in a perfectly spherical manner; that is, there is some difference in pressure off the nose, tail, and sides, but for practical purposes, the assumption that the energy spreads out evenly in all directions is justified.

8-2 PEAK OVERPRESSURE

The physical characteristics of a shock wave are usually measured by the peak overpressure and impulse of the positive phase at various distances from the point of explosion. The peak pressure is the pressure jump at the shock front, the highest pressure in the shock wave, and it is usually measured in pounds per square inch above atmospheric pressure. The positive phase is usually of very short duration; for example, about 0.0008 seconds at 10 feet from a 100-lb GP bomb, and 0.05 seconds at 400 feet from a 4000-lb LC bomb. The negative phase lasts considerably longer (5 or 6 times the positive phase) but the maximum negative pressure is only a fraction of the maximum positive pressure.

Ballistic data for specific weapons tabulate peak pressures (side-on) and positive impulses. Pressures registered by a pressure gauge placed side-on to the direction of blast are commonly referred to as the hydrostatic or side-on pressures. The pressure that would be registered by a gauge set face-on to the blast would be more than twice the side-on pressure owing to the reflection of the shock wave. At points relatively close to the bomb, where the peak pressures are high, the pressure registered by a face-on gauge woud be considerably more than twice the side-on pressure because of the wind effect, i.e., the actual movement of the air in the direction away from the explosion. Near the explosion where the wind is great, it will be strong enough to hurl even large objects for considerable distances. Where the side-on pressure is only 5 lb per square inch, the face-on will be about twice as large; whereas for a side-on pressure of 100 lb per square inch, the face-on pressure will be five times as large.

The peak pressure existing in a shock wave decreases rapidly as the shock wave moves outward from the center of explosion. Among the factors contributing to this decrease in pressure are the irreversible heating of air passing through the shock front and thereby extracting energy from it; and the increasing surface area of the shock front which reduces the energy per unit area (expanding sphere).

If r represents the distance from the center of the explosion to the point of peak pressure, the following laws approximate the effect of increasing distance:

(a) Close to the center of explosion where pressure exceeds 10 lb per square inch, peak pressure varies roughly as $1/r^2$.

(b) Farther from the center of explosion where peak pressure has dropped to the range of 5 to 10 lb per square inch, peak pressure varies as $1/r^{3/2}$.

(c) At considerable distance from the center of explosion where peak pressure is below 1 lb per square inch, peak pressure varies approximately as $1/r^{6/5}$.

Figure 8-3 shows a plot of peak blast pressure versus distance from the point of detonation for various sizes of high explosive bombs. Note that different sizes of bombs will produce the same peak pressure at different distances. This may be compared with the effects of a 20-KT yield air burst atomic weapon where an overpressure of 5 psi or greater extends to a distance of 6000 feet from ground zero.

Peak pressure may be related to charge weight (w) or yield (Y) of an explosion, as a measure of the amount of energy released. The effects of two different weights or yields of explosive charge may be related as follows:

For chemical reactions, the peak pressures will be equal at distances that are in the ratio of the cube root of the weights; i.e., if the pressure from a charge of w_1 lb is P_1 lb per square inch at distance r_1 feet, then for a weight of w_2 lb the

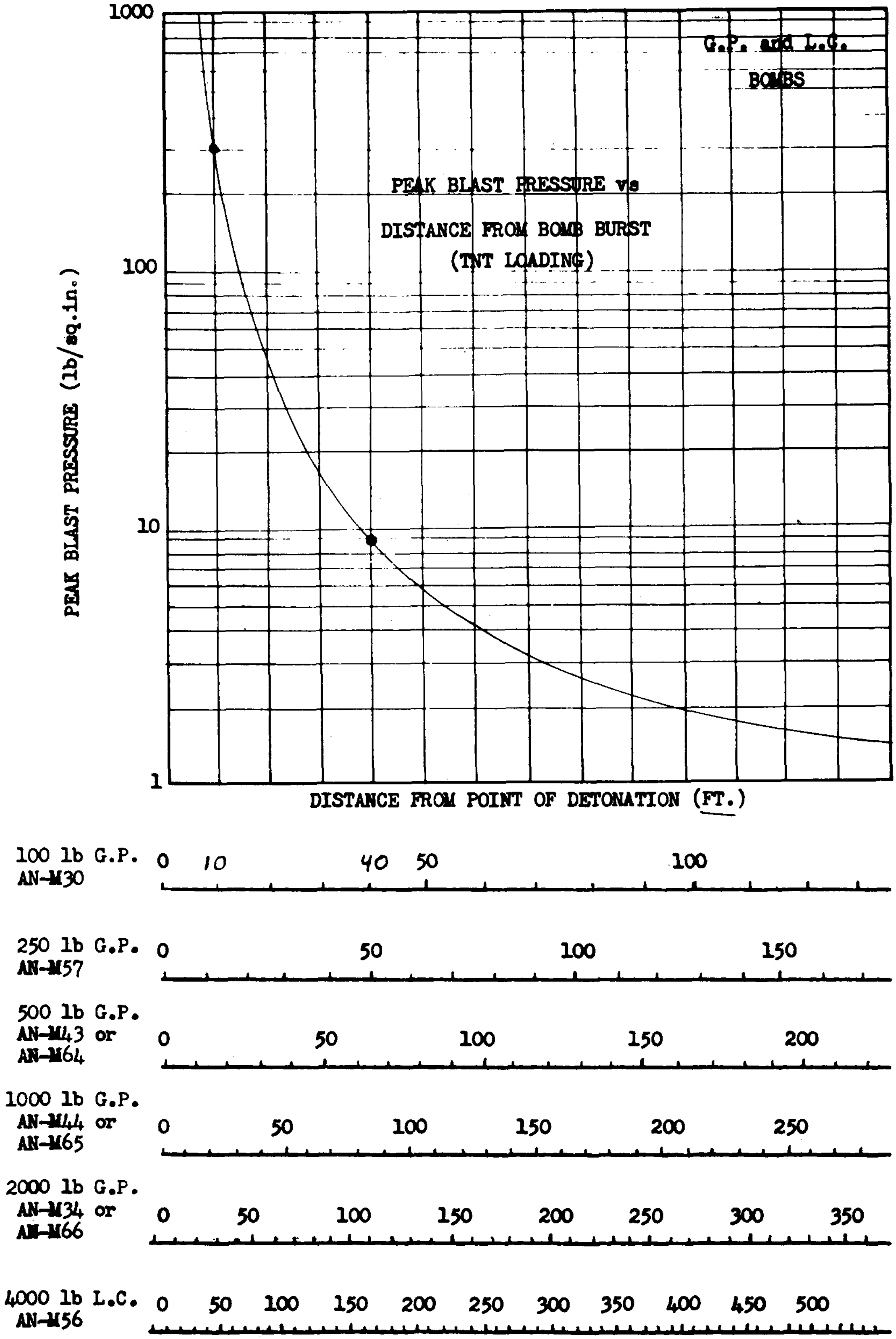

Fig. 8-3 Peak blast pressure versus distance from bomb burst.

TABLE 8-1 RELATIVE BLAST EFFECTIVENESS OF VARIOUS EXPLOSIVES, TNT = 100*

Explosive	Peak Pressure (at Equal Distances)	Effectiveness Against Load-Bearing Wall Construction	
		Radius	Area
Torpex (RDX/TNT/AL: 42/40/18)	122.5	125	156
HBX (RDX/TNT/AL/Wax: 40/38/17/5)	117.5	120	144
Minol (NH_4NO_3/TNT/AL: 40/40/20)	115	117.5	138
Tritonal (TNT/AL: 80/20)	112.5	117.5	138
DBX (NH_4NO_3/RDX/TNT/AL: 21/21/40/18)	112.5	112.5	127
RDX Comp B (RDX/TNT: 60/40)	110	110	121
Ednatol (Halite/TNT: 57/43)	105	105	111
TNT	100	100	100
Picratol (Expl. D/TNT: 52/48)	100	100	100
Amatex (NH_4NO_3/RDX/TNT: 43/9/48)	100	97.5	95
Amatol (NH_4NO_3/TNT: 50/50)	95	87.5	77

* Extracted from TM 9-1907, dated July 1948.

pressure will be P_1 lb per square inch at a distance r_2 feet where

$$r_2 = r_1 \left(\frac{w_2}{w_1}\right)^{1/3}$$

For nuclear reactions

$$r_2 = r_1 \left(\frac{Y_2}{Y_1}\right)^{1/3}$$

The data in Figure 8-3 refer to TNT fillings. The relative blast effectiveness of other explosives is indicated in Table 8-1.

8-3 THE EFFECT OF MACH REFLECTION ON AIR BURSTS

While consideration must be given to underground, underwater, and surface bursts as well, it is of major importance in the discussion of overpressure to recognize that when a bomb is detonated at some distance above the ground, the shock wave spreads out almost spherically until it strikes the ground. It is reflected by the ground surface as shown in Figure 8-4. At a certain distance along the ground from the point immediately below the bomb, the reflected wave combines with the original shock wave, called the incident wave, to form a third wave which has a vertical front at ground level. The third wave is called a Mach wave and the point where the three waves intersect, the triple point. The Mach wave grows in height as it spreads laterally, and the triple point rises, describing a curve through the air. The point of origin and path of the triple point depend on the size of the explosive charge and its height above the ground. At the triple point, where the incident wave is reinforced by the reflected wave, both the peak pressure and

MACH REFLECTION

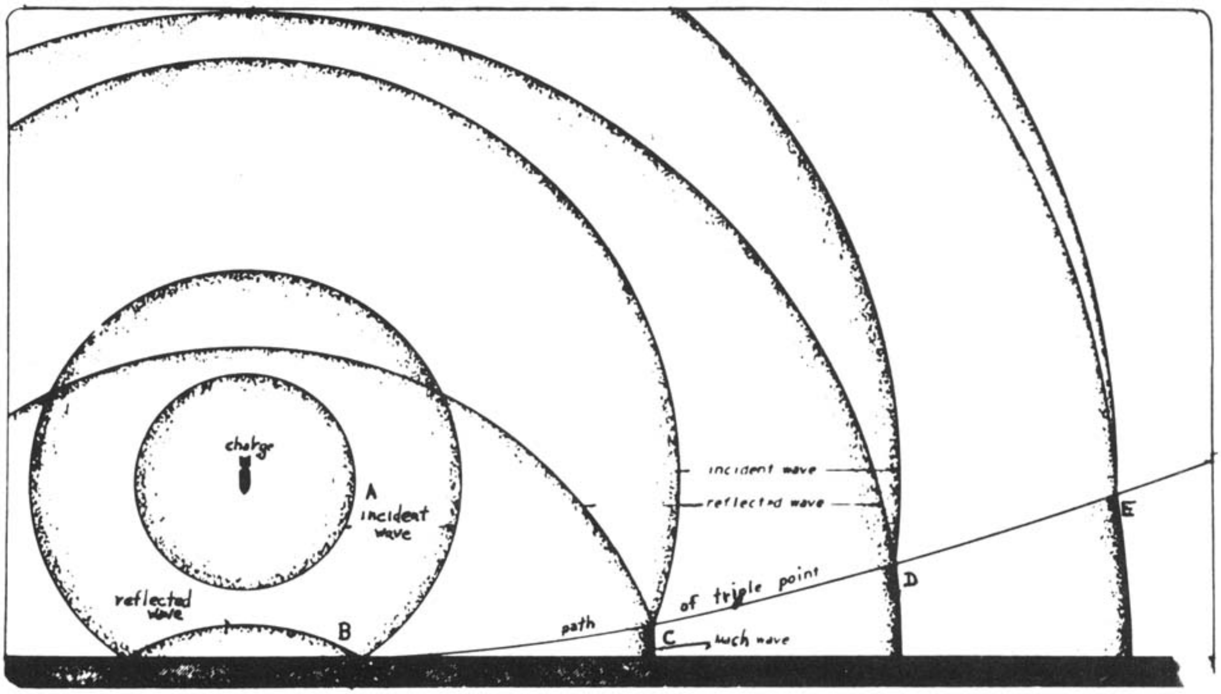

Fig. 8-4 Formation of Mach wave and triple point.

impulse are a maximum, and considerably higher than that exerted by the original shock wave at the same distance from the point of explosion.

As the Mach wave grows in height it absorbs the incident and reflected waves. Ultimately, at distances very large compared to the height of burst, the whole configuration of shocks becomes approximately a single spherical shock wave intersecting the ground perpendicularly.

Utilizing this phenomenon of Mach reflection makes it possible to increase considerably the radius of effectiveness of a bomb. By detonating a weapon at the proper height above the ground the maximum radius at which a given pressure or impulse is exerted can be increased in some cases by almost 50% over that for the same bomb detonated at ground level. The area of effectiveness is thereby increased by as much as 100% under some conditions. Ballistic data are used to determine the height of burst necessary to maximize the horizontal distance at which a given impulse can be obtained.

The optimum height for an air burst, and the amount by which its effectiveness will be increased depend on the size of bomb, and the strength and height of the target structure. The use of air burst on some types of targets, such as city areas, also tends to increase the area of effectiveness of a blast bomb by reducing the shielding effect that buildings and other structures have on one another.

8-4 IMPULSE

As indicated in Figure 8-1, a physical characteristic of a shock wave that is of basic importance, is the impulse of the positive phase. As a measure of both the intensity of the pressure and its duration, it is equal to the area under the pressure-time curve of the positive phase. It is approximately equal to one-half the peak pressure multiplied by the duration of the positive phase and is measured in units of pound-milliseconds per square inch. The impulse of an explosion will be equal at distances that vary as the two thirds power of the ratio of the weights

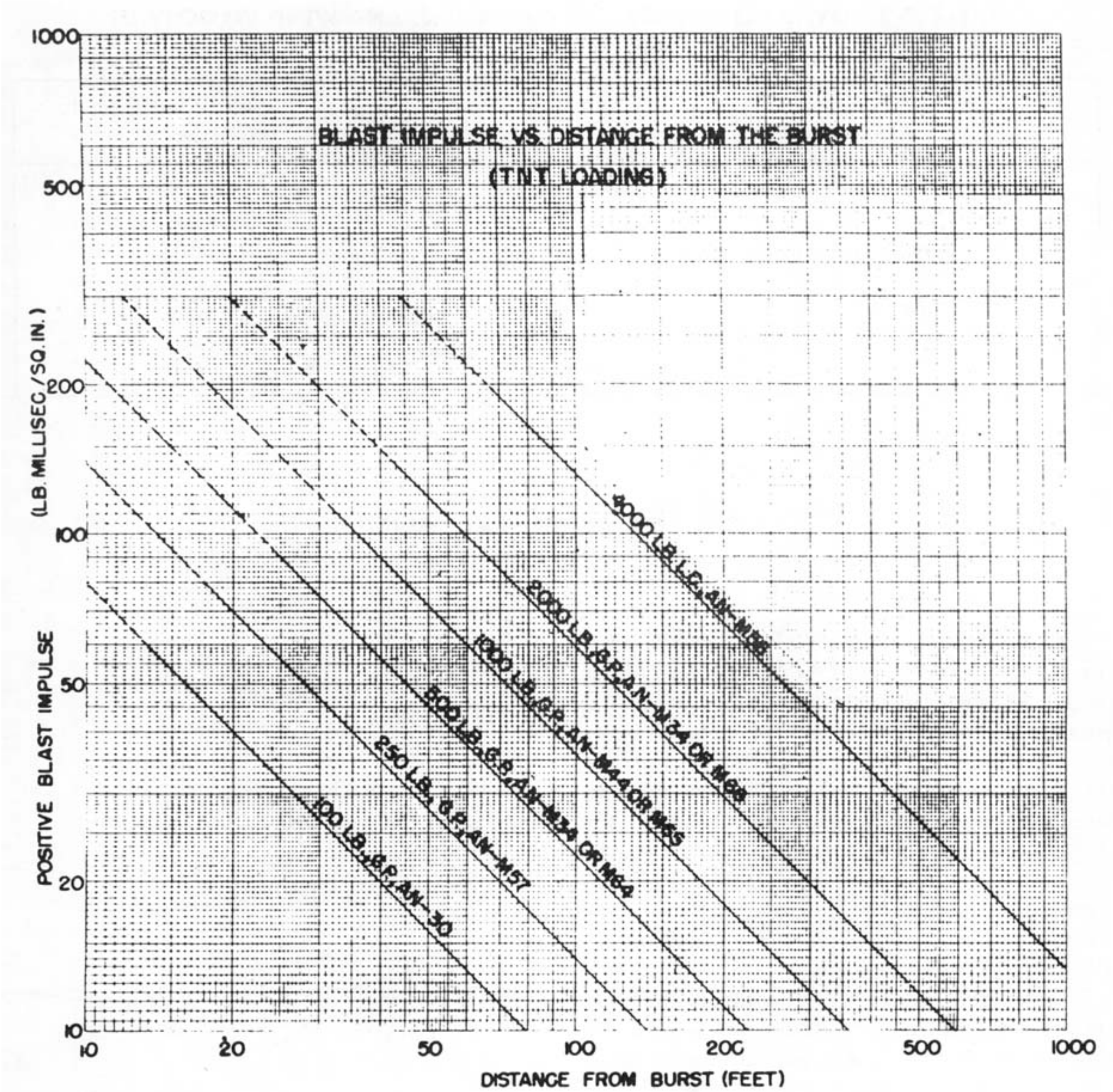

Fig. 8-5 Blast impulse versus distance from bomb burst.

or yields (Y); i.e., if the impulse from w_1 lb is I_1 lb-sec per square inch at r_1 feet, then the impulse from a charge of w_2 lbs will be equal to I_2 at a distance r_2 such that

$$r_2 = r_1 \left(\frac{w_2}{w_1}\right)^{2/3} \quad \text{or} \quad r_2 = r_1 \left(\frac{Y_2}{Y_1}\right)^{2/3}$$

Provided minimum values of impulse required to destroy a specific type of structure are known, the radii to which these values are satisfied as a function of explosive charge weight or yield can be determined from the above relationships. A sample tabulation of blast impulse for bombs is shown in Figure 8-5.

TABLE 8-2 OVERPRESSURE, DYNAMIC PRESSURE, AND WIND VELOCITY IN AIR AT SEA LEVEL

Peak Overpressure (pounds per square inch)	Peak Dynamic Pressure (pounds per square inch)	Maximum Wind Velocity (miles per hour)
72	80	1,170
50	40	940
30	16	670
20	8	470
10	2	290
5	0.7	160
2	0.1	70

8-5 DYNAMIC PRESSURE

Although the destructive effects of the blast wave have usually been related to values of the peak overpressure, there is another quantity of equivalent importance called the dynamic pressure ($q = \frac{1}{2}\rho u^2$). For a great variety of building types, the degree of blast damage depends largely on the drag force associated with the strong (transient) winds accompanying the passage of the blast wave. The drag force is influenced by certain characteristics (primarily the shape and size) of the structure, and is generally dependent upon impulse.

The dynamic pressure is a function of the wind velocity and the density of the air behind the shock front. Both of these quantities are related to the overpressure under ideal conditions at the shock front (see Par. 8-8). For very strong shocks, the dynamic pressure is larger than the overpressure, but below 69 pounds per square inch overpressure at sea level, the dynamic pressure is smaller. Like the peak shock overpressure, the peak dynamic pressure decreases with increasing distance from the explosion center, although at a greater rate. Some indication of the corresponding values of peak overpressure, peak dynamic pressure, and maximum blast wind velocities in air at sea level is given in Table 8-2.

At a given location, the dynamic pressure changes with time in a manner somewhat similar to the change in the overpressure, but the rate of pressure decrease behind the shock front is different. This may be seen from Figure 8-6 which indicates qualitatively how the two pressures vary in the course of the first second or so following arrival of the shock front. Actually, the wind velocity (and the dynamic pressure) will drop to zero at a somewhat later time, due largely to the inertia of the moving air, but for purposes of estimating damage the difference is not significant.

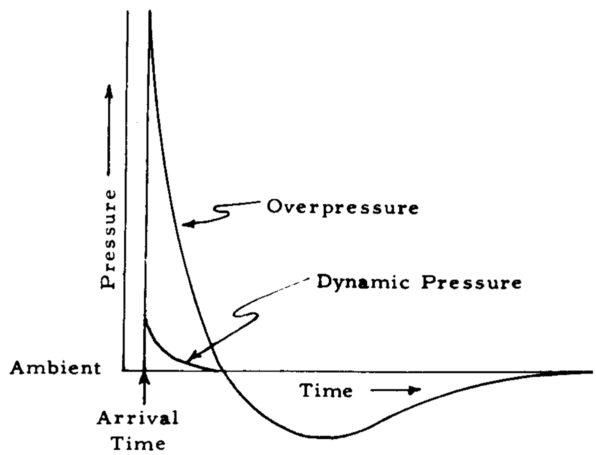

Fig. 8-6 Variation of overpressure and dynamic pressure with time at a fixed location.

8-6 AIR BLAST LOADING

The behavior of an object or structure exposed to the blast wave from a nuclear explosion may be considered under two main headings. The first is called the loading, i.e., the forces which result from the action of the blast pressure. The second is the response, or distortion of the structure due to the particular loading. As a general rule, response may be taken to be synonymous with damage since permanent distortion of a sufficient amount will impair the usefulness of a structure. Damage may also arise from a movable object striking the ground or another object which is more or less fixed. For example, tumbling vehicles are damaged primarily as they strike the ground. Further, glass, wood splinters, bricks, pieces of masonry, and other objects loosened by the blast wave and hurled through the air form destructive missiles. Indirect damage of these types is, of course, greatly dependent upon circumstances.

Direct damage to structures due to air blast can take various forms. For example, the blast may deflect structural steel frames, collapse roofs, dish-in walls, shatter panels, and break windows. In general, the damage results from some type of displacement (or distortion) and the manner in which such displacement can arise as the result of a nuclear explosion will be examined below.

For an air burst, the direction of propagation of the incident blast wave will be perpendicular to the ground at ground zero. In the regular reflection region, the forces exerted upon structures will also have a considerable vertical component (prior to passage of the reflected wave). Consequently, instead of the loading being largely lateral (or sideways) in nature, as it is in the Mach region, there will also be an appreciable downward force initially, which tends to cause crushing toward the ground, e.g., dished-in roofs, in addition to distortion due to translational motion.

8-7 DIFFRACTION LOADING

When the front of an air pressure wave strikes the face of a building, reflection occurs. As a result, the overpressure builds up rapidly to at least twice (and generally several times) that of the incident shock front. The actual pressure attained is determined by various factors such as the strength of the incident shock and the angle between the direction of motion of the shock wave and the face of the building. As the shock front moves forward, the overpressure on the face drops rapidly toward that produced by the blast wave without reflection. At the same time, the air pressure wave bends or diffracts around the structure so that the structure is eventually engulfed by the blast, and approximately the same pressure is exerted on all the walls and the roof.

The developments described above are illustrated in a simplified form in Figure 8-7. This shows, in plan, a building which is being struck by an air blast (Mach) wave moving in a horizontal direction. In Figure 8-7 the shock front is seen approaching the structure with the direction of motion perpendicular to the face of the building exposed to the blast. In Figure 8-7b the wave has just reached its front face, producing a high overpressure. In Figure 8-7c the blast wave has proceeded about half way along the building, and in Figure 8-7d it has reached the back. The pressure on the front face has dropped to some extent and it is building up on the sides as the blast wave diffracts around the structure. Finally, when as in Figure 8-7e the shock front has passed, approximately equal air pressures are exerted on all the walls (and roof) of the structure. If the structure is oriented at an angle to the blast wave, the pressure would immediately be exerted on two faces, instead of one, but the general behavior would be the same as just described (Figures 8-7f, g, h, and i).

The damage caused during the diffraction stage will be determined by the magnitude of the loading and by its duration. The loading is related

to the peak overpressure in the blast wave and this is consequently an important factor. If the structure under consideration has no openings, as has been tacitly assumed so far, the duration of the loading will be very roughly the time required for the shock front to move from the front to the back of the building. The size of the structure will thus affect the diffraction loading. For a structure 75 feet long, the diffraction loading will operate for a period of the order of one-tenth of a second. For thin structures, e.g., telegraph or utility poles and smokestacks, the diffraction period is so short that the corresponding loading is negligible.

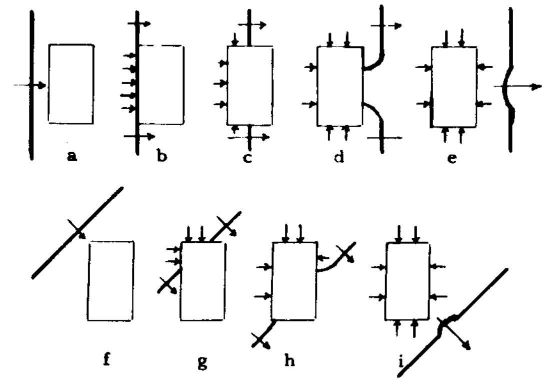

Fig. 8-7 Stages in the diffraction of a blast wave by a structure.

8-8 DRAG (DYNAMIC PRESSURE) LOADING

During the whole period that the positive phase of the air pressure wave is passing (and for a short time thereafter) a structure will be subjected to the dynamic pressure loading, or drag loading, caused by the strong transient winds behind the shock front. Like the diffraction loading the drag loading, especially in the Mach region, is equivalent to a lateral (or translational) force acting upon the structure or object exposed to the blast.

It is the effect of drag loading on structures which constitutes an important difference between nuclear and high explosive detonations. For the same peak overpressure in the blast wave, a nuclear bomb will prove to be more destructive than a conventional bomb, especially for buildings which respond to drag loading. This is because the blast wave is of much shorter duration for a high explosive bomb, e.g., a few thousandths of a second. Because of the increased length of the positive phase of the blast wave from weapons of high energy yield, such weapons cause more destruction than might be expected from the peak overpressures alone.

8-9 TECHNICAL ASPECTS OF BLAST WAVE PHENOMENA

The characteristics of the blast wave have been discussed in a qualitative manner in the earlier parts of this chapter. The remaining sections will be devoted to a consideration of some of the quantitative aspects of blast phenomena in air. The basic relationships among the properties of a blast wave, having a sharp front at which there is a sudden pressure discontinuity, are derived from the Rankine-Hugoniot conditions based on the conservation of mass, energy, and momentum at the shock front. These conditions, together with the equation of state for air, permit the derivation of the required relations involving the shock velocity, the particle (or wind) velocity, the overpressure, the dynamic pressure, and the density of the air behind the ideal shock front.

The blast wave properties in the region of regular reflection are somewhat complex and depend on the angle of incidence of the wave with the ground and the shock strength. For a contact surface burst, when there is but a single hemispherical (fused) wave, and in the Mach region below the triple point path for an air burst, the various blast wave characteristics at the shock front are uniquely related. It is for these conditions, in which there is a single shock front, that the following results are applicable.

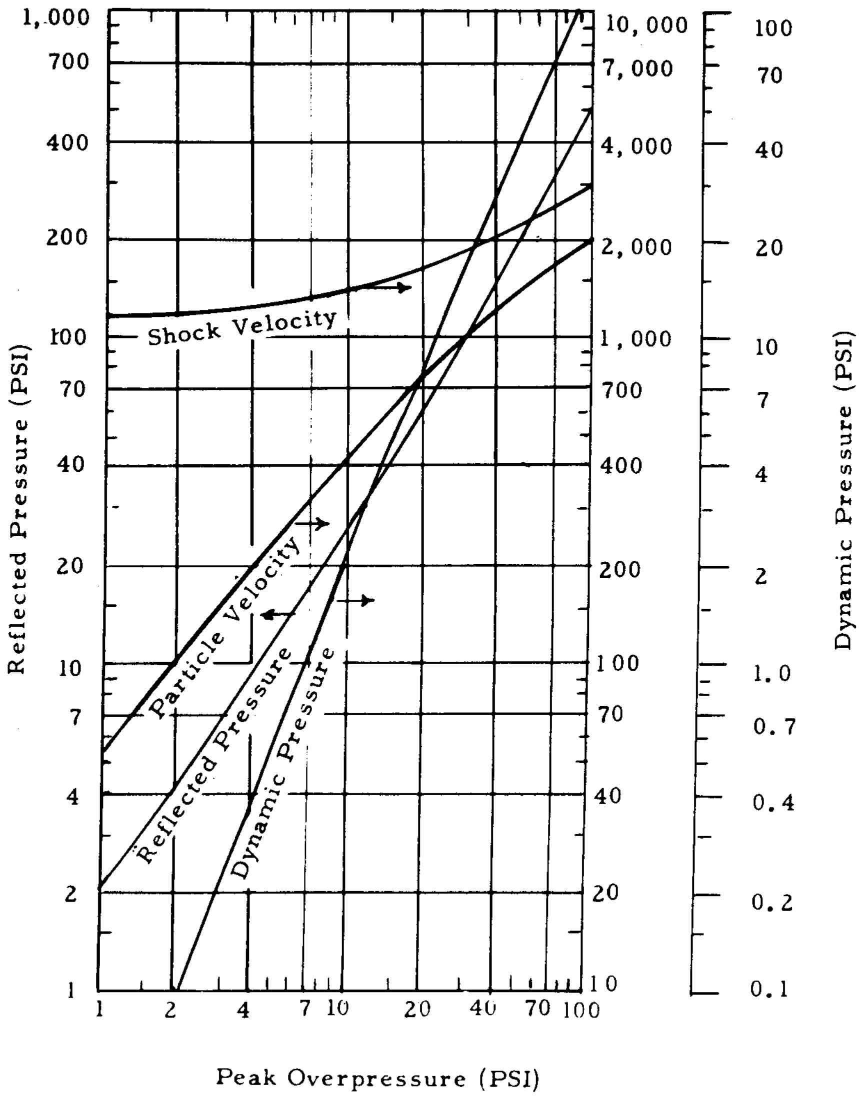

Fig. 8-8 Relation of blast wave characteristics at the shock front.

The shock velocity U, and the particle velocity (or peak wind velocity behind the shock front) u, are expressed by

$$U = a_0 (1 + 6p/7P_0)^{1/2}$$

and

$$u = \left(\frac{5p}{7P_0}\right)\left[\frac{a_0}{(1 + 6p/7P)^{1/2}}\right]$$

where p is the peak overpressure (behind the shock front), P_0 is the ambient pressure (ahead of the shock), and a_0 is the ambient sound velocity (ahead of the shock). The density, ρ, of the air behind the shock front is related to the ambient density, ρ_0, by

$$\frac{\rho}{\rho_0} = \frac{7 + 6p/P_0}{7 + p/P_0}$$

The peak dynamic pressure q, is defined as

$$q = \frac{5}{2} \cdot \frac{p^2}{7P_0 + p}$$

The variations of shock velocity, particle (or peak wind) velocity, and dynamic pressure with the peak overpressure at sea level, as derived from the foregoing equations, are shown graphically in Figure 8-8.

When the blast wave strikes a surface, such as that of a structure, at normal incidence, i.e., head on, the instantaneous value of the reflected overpressure, p_r, is given by

$$p_r = 2p\left(\frac{7P_0 + 4p}{7P_0 + p}\right)$$

It can be seen from this expression that the value of p_r approaches $8p$ for large values of the incident overpressure (strong shocks) and tends toward $2p$ for small overpressures (weak shocks) (see Figure 8-8).

8-10 ALTITUDE CORRECTIONS

The foregoing equations apply to a strictly homogeneous atmosphere, that is, where ambient pressure and temperature at the burst point and target are the same for all cases. If the ambient conditions are markedly different for a specified explosion, as compared with those in the reference explosion, then correction factors must be applied. The general relationships which take into account the possibility that the absolute temperature, T, and ambient pressure, P, are not the same as T_0 and P_0, respectively, in a reference (1-kiloton) explosion, are as follows. For the overpressure,

$$p = p_0\left(\frac{P}{P_0}\right)$$

where the p's refer to the respective overpressures at a given distance. The corrected values of distance for a specified pressure are then given by

$$d = d_0\,(W)^{1/3}\left(\frac{P_0}{P}\right)^{1/3}$$

and for arrival time or positive phase duration at the appropriate scaled distance by

$$t = t_0\,W^{1/3}\left(\frac{P_0}{P}\right)^{1/3}\left(\frac{T_0}{T}\right)^{1/2}$$

8-11 BLAST EFFECTS FROM NUCLEAR WEAPONS

Because the most severe blast effects on personnel, equipment, and structures come as a result of atomic detonations, such effects will be illustrated for atomic weapons.

8-11.1 PERSONNEL

Personnel can be injured by blast in two ways. Primary blast injuries resulting from the direct action of the blast overpressures on the human body, and secondary injuries resulting from flying debris. It requires approximately 100 psi overpressure to cause significant primary injury. Overpressures of this magnitude are not experienced even at ground zero from an air burst weapon and at very short distances from ground zero from surface burst weapons. Therefore, primary blast injuries are not significant from the point of view of personnel casualties. Secondary blast injuries are caused principally by collapsing buildings and debris or equipment flung about by the blast, or by the persons being picked up and hurled against stationary objects or the ground by the high winds accompanying the detonation. For instance, a 5 psi overpressure is accompanied by wind gusts up to 160 mph peak velocity. Secondary blast injuries are similar in effect to those due to mechanical accidents or blast from high explosive detonations.

8-11.2 MILITARY EQUIPMENT

All types of equipment can be damaged by blast if the peak overpressures are high enough. Wheeled vehicle damage consists of frame distortion, and wheel, body, and engine damage. The rupture of fuel tanks may cause fire to occur. Overturning contributes to the damage. Armored vehicles are very resistant to blast damage. However, even these vehicles may be damaged in the areas of very high peak manner

TABLE 8-3 BLAST EFFECTS RADII IN YARDS FROM GROUND ZERO

Weapon Yield	Type Burst	Built-up Areas and Personnel Therein	Command Posts	Military Vehicles	Tanks and Artillery
2 KT	*High Air	800	1400	negligible	negligible
	**Low Air	600	1100	500	200
20 KT	High Air	1800	3000	negligible	negligible
	Low Air	1300	2300	1100	450
100 KT	High Air	3000	5100	negligible	negligible
	Low Air	2300	3800	1900	750
500 KT	High Air	5200	8800	negligible	negligible
	Low Air	3900	6700	3300	1300
5 MT	Low Air	8300	14,000	7200	2800
	Surface	8300	14,000	7200	2800

*High Air Burst. This height of burst in this table is based on 2000 feet for the 20-KT weapon. Normally height of burst is scaled as the cube root of the ratio of yields.
**Low Air Burst. This height of burst in this table is based on one and one-half times the fireball radius for the 20-KT weapon or 675 feet. For other yields it has been assumed that fireball volume is directly proportional to yield.

as are tanks (Table 8-3). Lighter weapons and field equipment, since they are more easily blown about, are damaged at greater distances from a burst than is artillery. Aircraft in flight may be seriously damaged if engulfed by a blast wave. The gust loads resulting from the wind as well as the overall squeezing effect my cause intolerable structural damage.

8-11.3 STRUCTURES

Buildings and structures react to blast in a manner determined by their type of construction, design, strength, size, and the peak overpressures to which they are subjected. The drag characteristics of the target will be a function of resulting damage. Collapse of structures, particularly light masonry and brick, produces the greatest number of incapacitating (secondary) injuries to personnel in and around these structures.

8-11.4 CRATERING

A characteristic of all explosives detonated on the surface or under the ground is the formation of a crater; however, the particular result of nuclear explosions should be examined in somewhat closer detail. The mechanical energy of the expanding fireball throws earth upward and outward. The heavier particles of earth and rock fall back into and in the vicinity of the crater. This results in high radioactive contamination in the crater area. Some of the energy of the expanding fireball is dissipated into the earth itself as a shock wave in the ground. The effects of the ground shock wave are similar to a mild earthquake but are more localized. Destruction of underground structures is complete in the crater itself, and militarily significant damage caused by ground shock may extend beyond the crater for considerable distance. How far, depends on soil characteristics, type of structure, and yield of the weapon. Table 8-4 shows crater dimensions for the various nuclear weapons capable of being burst on or under the surface of land targets.

TABLE 8-4 CRATER DATA

Weapons (Yield)	Type of Burst	Crater Dimensions in Average Soil		Radius of Ground Shock in Average Soil (yd)
		Radius (yd)	Depth (ft)	
20-KT	surface	140	210	280
20-KT	underground	170	450	400
1-MT	surface	515	765	1450
5-MT	surface	880	1305	2500

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1 Oldenberg, *Introduction to Atomic Physics*, McGraw-Hill Book Co., N.Y., Chapter 19.

2 *Effects of Atomic Weapons*, Department of the Army Pamphlet 39-3, May 1957.

CHAPTER 9

THERMAL AND NUCLEAR EFFECTS OF ATOMIC DETONATIONS

9-1 INTRODUCTION

When an atomic weapon detonates in the air, a large sphere of hot, luminous gases is formed. This is called the fireball. The size of the fireball depends on the yield. The fireball from a nominal 20-KT weapon is about 300 yards across at maximum size and is about 30 times as brilliant as the sun at noon. Initially, the fireball contains all the energy of the detonation. Because of the very high temperature of the fireball, it radiates its heat (and light) out into the target area. The heat and light are referred to as thermal radiation; its emission from the fireball occurs in the first few seconds of detonation. For one test shot in Nevada the flash of light was observed 400 miles away.

The detonation process releases large amounts of nuclear radiation in the form of gamma radiation, alpha particles, beta particles, and neutrons. This nuclear radiation is emitted or radiated from the fireball in the first moments of the detonation. Most of it appears in the target area in the first two seconds after detonation; after one minute no significant nuclear radiation is received in the target area. The fireball continues to give off nuclear radiation, principally gamma radiation, for some time, but after one minute the fireball has risen so high that the gamma radiation does not reach the ground. The nuclear radiation which emanates from the fireball in the first minute or so after the detonation is called instantaneous nuclear radiation.

As the hot fireball expands rapidly in the first moments of detonation, it pushes a large volume of air outward. This outward push generates a blast wave in the air which continues to travel in the air with a velocity approximately equal to the speed of sound. The initial rapid rate of rise of the fireball causes air to be drawn inward and upward. Dust and dirt from the target surface are also drawn up to form the stem of the atomic cloud (see Figure 9-1). Approximately half of the energy of the detonation appears as blast; one-third as thermal radiation; and the rest as nuclear radiation. The characteristics of these principal weapon effects will be discussed in subsequent sections. Shortly after detonation the fireball rises and cools. Its rate of rise is quite rapid and it reaches a high altitude in a few minutes. The cooling and condensing of the fireball results in the mushroom head of the familiar atomic cloud.

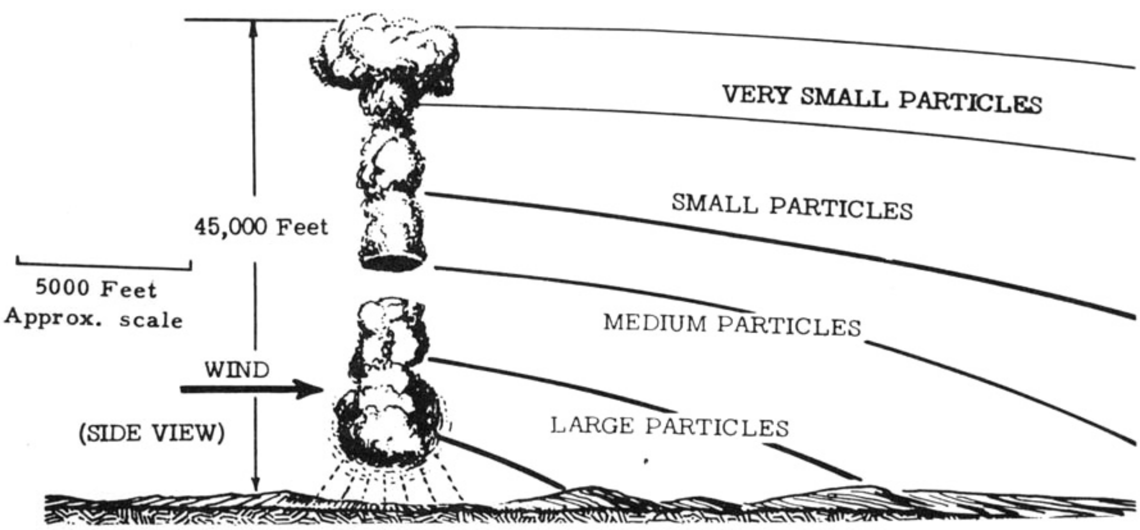

Fig. 9-1 Air burst of atomic bomb (20-KT).

9-2 UNDERGROUND BURST

When an atomic weapon is detonated below the earth's surface, the expansion of the fireball imparts to the surrounding earth a force upward and outward. A large volume of the earth is thrown out, leaving a crater. Some of the earth falls back into and around the crater. The fireball vents up through the ground; however, by the time it comes up through the surface, the fireball has given up most of its mechanical shock energy to the ground in the formation of a crater. Therefore, air blast resulting from an underground burst is very much less than from an air burst. Except for a relatively weak flash that appears when the fireball vents the surface, almost all the heat and light (thermal radiation) is released into the ground in an underground burst. Hence, above ground, thermal effects may be small or negligible.

The nuclear radiation products released by the detonation process are entrapped or absorbed by the ground. The soil which absorbs the nuclear radiation is thrown upward and outward. When it falls back to the ground it contaminates the area with residual radioactivity. From an underground burst, then, there is in the target area no significant thermal radiation, greatly reduced blast effects, cratering, and no instantaneous nuclear radiation.

When the earth in the vicinity of an underground burst is thrown upward, it produces a column of characteristic appearance. The heavier particles in the column fall back to earth and produce a concentric cloud of dust which expands outward from the burst point. This cloud is called the base surge. The finer dust particles of the column remain suspended in the air as a cloud for some time before eventually falling to earth. The atomic cloud from an underground burst does not rise as high as the cloud from an air burst; moreover, it is colored by the fine particles of soil entrapped in it.

9-3 SURFACE BURST

The characteristics of a land surface burst are, in general, intermediate between those of an air burst and an underground burst. Consider first a contact surface burst on land. Since the fireball, in a surface burst, forms above the ground, its rapid expansion generates a blast wave. However, some of the mechanical energy of the expanding fireball is transmitted to the earth under the fireball so that air blast from a surface burst differs from air blast from an air burst. Since the weapon detonates close to the earth, the air blast is very strong near the burst point but the blast pressures fall off more rapidly with increasing distances from burst point. Some cratering, however, will be accomplished. A 20-KT yield bomb detonated on the surface would produce a crater about 75 feet deep and 100 yards in diameter.

The thermal characteristics of a surface burst are essentially the same as for an air burst, i.e., just about as much heat and light are radiated in each case for weapons of the same yield. The area of effectiveness of thermal radiation in a target area is less from a surface burst than from an air burst. This is due to the fact that thermal radiation from a surface burst weapon arrives in the target at very acute angles of incidence and minor terrain irregularities, buildings, and even equipment provide effective shielding.

The instantaneous nuclear radiation emanating from the fireball of a surface burst weapon is essentially the same as from an air burst weapon of the same yield. However, since the fireball expands against the earth's surface, a considerable portion of the earth under the detonation is vaporized and irradiated. This vaporized irradiated earth is drawn up by the rising fireball. The combination of vaporization of a portion of the earth's surface and the scooping effect of the expanding fireball produces a crater, similar to but smaller in size than the crater from an underground burst. The heavier particles of rock and soil thrown out by a surface burst will fall back around the burst area. Since the soil has been irradiated it will contribute to residual radioactivity in the area. The vaporized earth drawn up into the fireball will condense when the fireball cools; fall to earth downwind, producing residual radioactivity in the area of fallout.

9-4 BURSTS IN OR OVER WATER

When an atomic weapon is burst in the air over water, the blast, thermal radiation, and instantaneous nuclear radiation are essentially the same as for an air burst over land.

When an atomic weapon is detonated under the surface of a body of water, the column thrown upward consists of water, or if the underwater burst occurs in shallow water, earth from the bottom. The column of water falling back onto the surface produces a base surge of mist and spray. Some of the energy of the fireball as it expands under water is transmitted to the water and is propagated outward as water shock and water waves on the surface. There is no appreciable thermal or instantaneous nuclear radiation from an underwater burst, and air blast is less than from an air burst. The water, thrown upward in the column, is irradiated and entraps fission fragments. When this water falls back to the surface, it contaminates the area with residual radioactivity (fallout). The base surge contributes to the residual radioactive contamination. If the fallout and base surge occur over large volumes of water, the residual radioactive contamination is soon diluted and dissipated. If the underwater burst occurs in a harbor or near enough to shore, the fallout may occur over land which would cause more concentrated contamination and would remain for longer periods.

When an atomic weapon detonates at or near the surface of water, the thermal instantaneous nuclear radiation and blast effects will be essentially those of a land surface burst. However, some of the mechanical energy of the expanding fireball will generate water waves and underwater shock. No crater will form unless the water is shallow. A large volume of water will be vaporized and drawn up into the cloud. When this condenses, it will be deposited as fallout.

9-5 CHARACTERISTICS OF THERMAL RADIATION

Most of the flash of light and heat from an atomic detonation is emitted in the first second of the detonation although some continues to be emitted as long as the ball of fire is visible. As has been mentioned, approximately one-third of the energy liberated in an atomic detonation is in the form of heat energy. In many cases the intense flash of light will be the first warning of an atomic detonation in the area but the thermal radiation will have already been emitted. The thermal radiation, like light, travels in straight lines and is stopped by any object or material which can cast a shadow. It has little penetrating power. Thus, even light-weight clothing may offer protection from such radiation.

As the thermal radiation travels outward from the fireball, it decreases in intensity. This reduction in intensity is due to absorption of the radiation by particles of dust, smoke, and haze in the air. The burning that might result from an atomic detonation, then, will be less when the air is hazy than if it is clear. A smoke screen, therefore, may be an effective shield in lessening the effects of thermal radiation from an atomic weapon.

Personnel who are facing in the general direction of an atomic detonation may experience a temporary blindness, called flash blindness. Essentially normal vision returns in a half hour or less. At night, even personnel facing away from an atomic detonation (eyes open and uncovered) may experience flash blindness but it will not persist as long as in personnel facing the detonation.

9-6 MECHANISM OF THERMAL RADIATION

Immediately after the ball of fire is formed, it emits thermal radiation. Because of the very high temperatures, this consists of ultraviolet (short wave length) as well as visible and infrared (long wave length) rays. Due to certain phenomena associated with the absorption of the thermal radiation by the air in front of the ball of fire, the surface temperature undergoes a curious change. The temperature of the interior falls steadily, but the surface temperature of the

ball of fire decreases more rapidly for a small fraction of a second. Then, the apparent surface temperature increases again for a somewhat longer time, after which it falls continuously. In other words, there are effectively two surface-temperature pulses; the first is of very short duration, whereas the second lasts for a much longer time. The behavior is quite general, although the duration times of the pulses increase with the energy yield of the explosion.

Corresponding to the two temperature pulses, there are two pulses of emission of thermal radiation from the ball of fire (Figure 9-2). In the first pulse, which lasts about a tenth part of a second for a one-megaton explosion, the temperatures are mostly very high. As a result, much of the radiation emitted in this pulse is in the ultraviolet region. Moderately large doses of ultraviolet radiation can produce painful blisters, and even small doses can cause reddening of the skin. However, in most circumstances, the first pulse of thermal radiation is not a significant hazard with regard to skin burns for several reasons. In the first place, only about one percent of the thermal radiation appears in the initial pulse because of its short duration. Second, the ultraviolet rays are readily attenuated by the intervening air, so that the dose delivered at a distance from the explosion may be comparatively small. Further, it appears that the ultraviolet radiation from the first pulse could cause significant effects on the human skin only within ranges at which other radiation effects are much more serious.

The situation with regard to the second pulse is, however, quite different. This pulse may last for several seconds and carries about 99 percent of the total thermal radiation energy from the bomb. Since the temperatures are lower than in the first pulse, most of the rays reaching the earth consist of visible and infrared (invisible) light. It is this radiation which is the main cause of skin burns of various degrees suffered by exposed individuals up to 12 miles or more from the explosion of a one-megaton bomb. For bombs of higher energy, the effective damage range is greater.

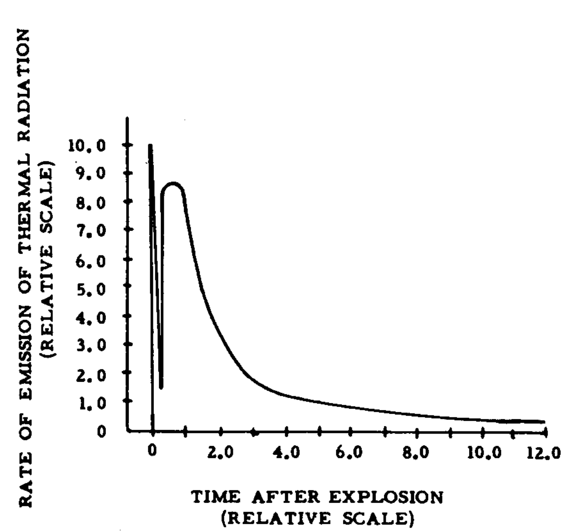

Fig. 9-2 Emission of thermal radiation in two pulses.

9-7 ATTENUATION OF THERMAL RADIATION

The extent of injury or damage caused by thermal radiation, or the chances of igniting combustible material, depend to a large extent upon the amount of thermal radiation energy received by a unit area of skin, fabric, or other exposed material. The thermal energy falling upon a given area from a specified explosion will be less the farther from the explosion, for two reasons: (1) the spread of the radiation over an ever-increasing area as it travels away from the fireball; and (2) attenuation of the radiation in its passage through the air. These factors will be considered in turn.

If the radiation is distributed evenly in all directions, then at a distance D from the explosion the same amount of energy will fall upon each unit area of the surface of a sphere of radius D. The total area of this sphere is $4\pi D^2$. If E is the thermal radiation energy produced in the explosion, the energy received per unit area at a distance D would be $E/4\pi D^2$, provided there were no attenuation by the atmosphere.

In order to estimate the amount of thermal energy actually reaching the unit area, allowance must also be made for the attenuation of the radiation by the atmosphere. This attenuation is

due to two main causes; namely, absorption and scattering. Atoms and molecules present in the air are capable of absorbing, and thus removing, certain radiations. Absorption is most effective for the short wave length (or ultraviolet) rays. In this connection, oxygen molecules and ozone play an important part. Although the proportion of ozone in the air is usually quite small, appreciable amounts of this substance are produced by the interaction of gamma radiation from the nuclear explosion with atmospheric oxygen.

Because of absorption, the amount of ultraviolet present in thermal radiation decreases markedly within a short distance from the explosion. At distances where thermal radiation effects are significant, compared with other effects (blast and initial nuclear radiation), the proportion of ultraviolet radiation is quite small.

Attenuation as a result of scattering, i.e., by the diversion of rays from their original paths, occurs with radiation of all wave lengths. Scattering can be caused by molecules, such as oxygen and nitrogen, present in the air. This is, however, not as important as scattering resulting from the reflection and diffraction (or bending) of light rays by particles, e.g., of dust, smoke, or fog, present in the atmosphere. The diversion of the radiation path due to scattering interactions leads to a somewhat diffuse, rather than a direct, transmission of the thermal radiation.

9-8 ABSORPTION OF THERMAL RADIATION

Of the two thermal radiation pulses emitted by the ball of fire, the first contains a larger proportion of ultraviolet rays, because of the very high temperatures existing during this period. It is known, from theoretical studies and experimental measurements, that the wave length corresponding to the maximum energy density of radiation from an ideal (or black body) radiator, to which the nuclear fireball is a good approximation, decreases with increasing temperature of the radiation. At temperatures above 7600°C (13,700°F), this maximum lies in the ultraviolet region of the spectrum. However, the first pulse lasts only a fraction of a second, even for explosions in the megaton energy range, and the amount of thermal energy emitted is a negligible proportion of the total. At distances from the detonation at which thermal radiation effects are important, the ultraviolet portion of the radiation is small because of the short time that the fireball surface temperature is very high, and the strong atmospheric absorption of the ultraviolet rays. Nevertheless, since these radiations have a greater capability for causing biological damage than visible or infrared rays, they may contribute to thermal injury in some circumstances.

Since only a small proportion of the heat is dissipated by conduction in the short time during which the radiation falls upon the material (except perhaps in good heat conductors such as metals) the absorbed energy is largely confined to a shallow depth of the material. Consequently, very high temperatures are attained at the surface. It has been estimated, for example, that in the nuclear explosions in Japan, which took place at a height of some 1850 feet, the temperature on the ground immediately below the burst was probably from 3000 to 4000°C (5400 to 7200°F). It is true that the temperature fell off rapidly with increasing distance from the explosion, but there is some evidence that it exceeded 1600°C (2900°F) even 4000 feet away.

The most important physical effects of the high temperatures resulting from absorption of thermal radiation are burning of the skin, and scorching, charring, and possibly ignition of combustible organic substances, e.g., wood, fabrics, and paper. Thin or porous materials, such as lightweight fabrics, newspaper, dried grass and leaves, and dry rotten wood, may flame when exposed to thermal radiation. On the other hand. thick organic materials, for example wood (more than ½-inch thick), plastics, and heavy fabrics char but do not burn. Dense smoke and even jets of flame may be emitted, but the material does not sustain ignition.

TABLE 9-1 APPROXIMATE THERMAL ENERGIES REQUIRED TO CAUSE SKIN BURNS IN AIR OR SURFACE BURST

Total Energy Yield	Thermal Energy (cal/sq cm)		
	First Degree	Second Degree	Third Degree
1 kiloton	2	4	6
100 kilotons	2½	5½	8
10 megatons	3½	7	11

9-9 BURN INJURY ENERGIES AND RANGES

The approximate thermal radiation energy required to produce moderate first-, second-, or third-degree burns as a result of exposure to nuclear explosions (in the air or at the surface) with total energy yields of 1 kiloton, 100 kilotons, and 10,000 kilotons (10 megatons), is given in Table 9-1. This energy is expressed in calories, and the unit area is taken as one square centimeter, so that the energies are given in calories per square centimeter (cal/sq cm) of skin area. There are some variations from the quoted energy values because of differences in skin sensitivity, pigmentation, and other factors affecting the severity of the burn.

It can be seen from Table 9-1 that the amount of thermal radiation energy required to produce a burn of any particular degree of severity increases with the total energy yield of the explosion. Thus, four calories per square centimeter will cause a second-degree burn in the case of a one-kiloton explosion, but for a ten-megaton burst, seven calories per square centimeter would be necessary. The reason for this difference lies in the fact that in the former case the thermal energy is received in a very short time, e.g., not more than a few tenths of a second, but in the latter case the effective delivery time may extend to several seconds. The greater the exposure time, the larger, in general, is the amount of thermal energy required to produce a particular effect.

Taking into consideration the variation of the heat energy requirement with the energy yield of the explosion, Figure 9-3 portrays the ranges for moderate first-, second-, and third-degree burns for nuclear explosions from one kiloton to 20 megatons energy yield. In deriving the curves, two particular assumptions have been made. First, it is supposed that the explosion occurs in the air at the same height as that to which the results on blast phenomena are applicable. For a surface burst, the distances would be scaled down to about 60 percent of those in the figure. Second, it is assumed that reasonably clear atmospheric conditions prevail, so that the attenuation is essentially independent of the visibility range as far out as ten miles or more from ground zero. If the atmosphere is hazy, the distances predicted in Figure 9-3, especially for the higher energy yields, may be somewhat in excess of the actual distances. They will certainly be too large if there is a substantial layer of cloud or smoke below the point of burst.

9-10 EFFECTIVENESS OF SECOND RADIATION PULSE

An important point to consider, especially from the standpoint of protection from thermal radiation, is the period during which the radiation is most effective in causing skin burns. It has been established that the proportion of the total thermal energy contained in the first radiation pulse emitted while the surface temperature of the fireball is dropping toward the first minimum (Figure 9-2), is small. However, it is still desirable to know whether the radiation emitted during

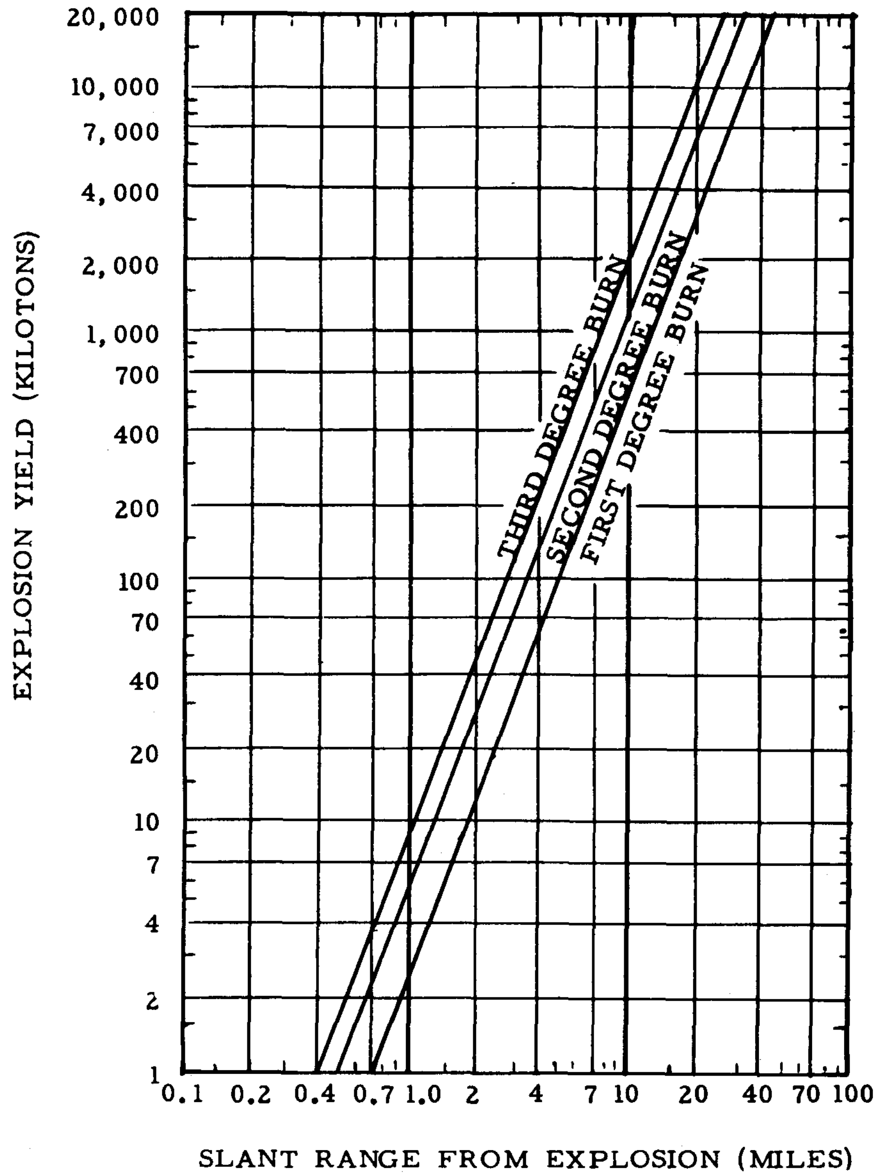

Fig. 9-3 Distances at which burns occur on bare skin.

the whole of the second pulse, from the minimum through the maximum and down to the second minimum, is significant.

Due to the decrease in thermal energy received per unit area at increasing distances from the fireball, more distant objects will receive less energy than those closer in. As objects are located farther and farther away from the explosion, the thermal energy received from all portions of the pulse is proportionately reduced, so that when the separation is great enough, no damage will be sustained. The part of the thermal pulse which can be most easily decreased to significance occurs toward the end, when the intensity of the ball of fire has become relatively low. Hence, at some distance from the explosion, the tail end of the thermal pulse may be ineffective in causing damage, although the high-intensity part, especially that around the temperature maximum, is still capable of

inflicting injury. Closer to the fireball, the tail of the pulse will also be dangerous and the high-intensity region will be even more so.

At all distances from the explosion, the most dangerous part of the thermal pulse is that which occurs around the time of the second temperature maximum of the fireball. It is here that the thermal radiation intensity of the ball of fire is greatest. Consequently, the rate at which energy is delivered to objects at any distance from the explosion is also greatest. In other words, from a given explosion, more thermal energy will be received in a certain period of time around the temperature maximum than at any other equal period during the thermal pulse.

These facts are important in relation to the efficacy of evasive action that might be taken by individuals to reduce injuries due to thermal radiation. From what has been stated above, it is apparent that it is desirable to take such action before the temperature maximum in the second thermal pulse is reached.

In the case of an explosion in the kiloton range, it would be necessary to take shelter within a small fraction of a second if an appreciable decrease in thermal injury is to be realized. The time appears to be too short for evasive action to be possible. On the other hand, for explosions in the megaton range, shelter taken within a second or two of the appearance of the ball of fire could reduce the severity of injury due to thermal radiation in many cases, and may even prevent injury in others.

Although personnel can sustain flash burns at relatively great distances from an atomic detonation, a number of factors tend to minimize the effectiveness of thermal radiation as a predictable mechanism for the production of casualties in a tactical unit. Clothing, particularly combat uniforms, provides considerable protection from thermal radiation except on exposed face and hands. From a 20-KT weapon, for example, personnel will not be burned through military clothing beyond 1,500 yards from ground zero. In contrast, third degree burns on exposed skin can be sustained out to 2200 yards, second degree burns out to 3000 yards.

Any shadow-producing object or terrain feature will provide protection from thermal radiation (though not necessarily from blast or nuclear radiation). An individual in a foxhole or trench, behind a tree, rock, or terrain irregularity, or even prone in a shallow fold in the ground will not be burned if the shielding object is between him and the fireball (see Table 9-2).

TABLE 9-2 THERMAL EFFECTS RADII IN YARDS FROM GROUND ZERO IN WHICH PERSONNEL CAN SUSTAIN INCAPACITATING BURNS

Weapon Yield	Type Burst	Troops in Foxholes	Troops in Open
2 KT	High Air	300	1000
	Low Air	400	1000
20 KT	High Air	600	2200
	Low Air	850	2200
100 KT	High Air	1100	4000
	Low Air	1400	4100
500 KT	High Air	1800	6900
	Low Air	2100	7000
5 MT	Low Air	4100	14,800
	Surface	4200	14,200

9-11 CHARACTERISTICS OF NUCLEAR RADIATION

The explosion of a nuclear bomb is associated with the emission of various nuclear radiations. These consist of neutrons, gamma rays, and alpha and beta particles. Essentially, all the neutrons and part of the gamma rays are emitted in the actual fission process: These radiations are produced simultaneously with the nuclear explosion. Some of the neutrons liberated in fission are immediately absorbed (or captured) by various nuclei present in the bomb, and this capture process is usually also accompanied by the instantaneous emission of gamma rays. The remainder of the gamma rays and the beta particles are liberated over a period of time as the fission products undergo radioactive decay. The alpha particles are expelled, in an analogous

manner, as a result of the decay of the uranium (or plutonium) which has escaped fission in the bomb.

The initial nuclear radiation is generally defined as that emitted from both the ball of fire and the atomic cloud within the first minute after the explosion. It includes neutrons and gamma rays given off almost instantaneously, as well as gamma rays emitted by the radioactive fission products in the rising cloud. It should be noted that although alpha and beta particles are present in the initial radiation, they have not been considered. This is because they are so easily absorbed that they will not reach more than a few yards at most, from the atomic cloud.

The somewhat arbitrary time period of one minute for the duration of initial nuclear radiation was originally based upon the following considerations: As a consequence of attenuation by the air, the effective range of the fission gamma rays and of those from the fission products from a 20-kiloton explosion is very roughly two miles. In other words, gamma rays originating from such a source at an altitude of over two miles can be ignored, as far as their effect at the earth's surface is concerned. Thus, when the atomic cloud has reached a height of two miles, the effects of the initial nuclear radiations are no longer significant. Since it takes roughly a minute for the cloud to rise this distance, the initial nuclear radiation was defined as that emitted in the first minute after the explosion.

The foregoing arguments are based on the characteristics of a 20-kiloton nuclear bomb. For a bomb of higher energy, the maximum distance over which the gamma rays are effective will be larger than that given above. However, at the same time, there is an increase in the rate at which the cloud rises. Similarly, for a bomb of lower energy, the effective distance is less, but so also is the rate of ascent of the cloud. The period over which the initial nuclear radiation extends may consequently be taken to be approximately the same, namely one minute, irrespective of the energy release of the bomb.

Neutrons are the only significant nuclear radiations produced directly in thermonuclear reactions. Alpha particles (helium nuclei) are also formed, but they do not travel very far from the explosion. Some of the neutrons will escape but others will be captured by the various nuclei present in the exploding bomb. Those neutrons absorbed by fissionable species may lead to the liberation of more neutrons as well as to the emission of gamma rays, just as described above for an ordinary fission bomb. In addition, the capture of neutrons in nonfission reactions is usually accompanied by gamma rays. It is seen, therefore, that the initial radiations from a bomb in which both fission and fusion (thermonuclear) processes occur consist essentially of neutrons and gamma rays. The relative proportions of these two radiations may be somewhat different than for a bomb in which all the energy release is due to fission; but for present purposes the difference may be disregarded. Although the energy of the initial gamma rays and neutrons is only about three percent of the total explosion energy, compared with some 33 percent appearing as thermal radiation, the nuclear radiations can cause a considerable proportion of the bomb casualties.

9-12 INITIAL GAMMA RADIATION

The gamma rays produced in fission, and as a result of other neutron reactions and nuclear excitation of the bomb materials, all appear within a second (or less) after the nuclear explosion. For this reason, the radiations from these sources are known as the prompt or instantaneous gamma rays.

The fission fragments and many of their decay products are radioactive isotopes which emit gamma radiations. The half lives of these radioactive species range from a millionth of a second (or less) to many years. Nevertheless, since the decay of the fission fragments commences at the instant of fission, and since, in fact, their rate of decay is greatest at the beginning, there will be an appreciable liberation of gamma radiation from these radioisotopes during the first minute after the explosion. In other words, the gamma rays emitted by the fission products make a significant contribution to the initial nuclear radiation. However, since the radioactive decay process is a continuing (or gradual) one, spread over a period of time which is long compared to that in which the instantaneous radiation is produced, the resulting gamma radiations are referred to as the delayed gamma rays.

The instantaneous gamma rays and the portion of the delayed gamma rays which are included in the initial radiation, are nearly equal in amount, but they are by no means equal fractions of the initial nuclear radiation transmitted from the exploding bomb. The instantaneous gamma rays are produced almost entirely before the bomb has completely blown apart. They are, therefore, strongly absorbed by the dense bomb materials, and only a small proportion actually emerges. The delayed gamma rays, on the other hand, are mostly emitted at a later stage in the explosion, after the bomb materials have vaporized and expanded to form a tenuous gas. These radiations thus suffer little or no absorption before emerging into the air. The net result is that the delayed gamma rays, together with those produced by the radiative capture of neutrons by the nitrogen in the atmosphere, contribute about a hundred times as much as do the prompt gamma rays to the total radiation received at a distance from an air (or surface) burst.

9-13 SOURCES OF NEUTRONS AND IONIZATION CHARACTERISTICS

Although neutrons are nuclear particles of appreciable mass, whereas gamma rays are electromagnetic waves analogous to X-rays, their harmful effects on the body are similar in character. Like gamma rays, only very large doses of neutrons may possibly be detected by the human senses. Neutrons can penetrate a considerable distance through the air and constitute a hazard that is greater than might be expected from the small fraction (about 0.025 percent) of the explosion energy which they carry.

Essentially, all the neutrons accompanying a nuclear explosion are released either in the fission or fusion process. All of the neutrons from the latter source and over 99 percent of the fission neutrons are produced almost immediately, probably within less than a millionth of a second of the initiation of the explosion. These are referred to as the prompt neutrons.

In addition, somewhat less than one percent of the fission neutrons, called the delayed neutrons, are emitted subsequently. Since the majority of these delayed neutrons are emitted within the first minute, however, they constitute part of the initial nuclear radiation. Some neutrons are also produced by the action of the gamma rays of high energy on the nuclear bomb materials. But these make a very minor contribution and so can be ignored.

Although the prompt fission neutrons are all actually released within less than a millionth of a second of the explosion, as noted above, they are somewhat delayed in escaping from the environment of the exploding bomb. This delay arises from the numerous scattering collisions suffered by the neutrons with the nuclei present in the bomb residues. As a result, the neutrons traverse a complex zigzag path before they finally emerge. They have fairly high speeds, but the actual (average) distance the neutrons travel is relatively large, and so some time elapse before they reach the outside of the ball of fire. However, the delay in the escape of the prompt neutrons is no more than about a hundredth part of a second.

Neutrons, being electrically neutral particles, do not produce ionization or excitation directly in their passage through matter. They can, however, cause ionization to occur indirectly as a result of their interaction with certain light nuclei. When a fast neutron collides with the nucleus of a hydrogen atom, for example, the neutron may transfer a large part of its energy to that nucleus. As a result, the hydrogen nucleus is freed from its associated electron and moves off as a high-energy proton. Such a proton is capable of producing a considerable number of ion pairs in its passage through a gas. Thus, the interaction of a fast neutron with hydrogen (or with any substance containing hydrogen) can cause ionization to occur indirectly. By a similar mechanism, indirect ionization, although to a smaller extent, results from collisions of fast neutrons with other light nuclei, e.g., carbon, oxygen, and nitrogen. (The ionization resulting from the interaction of fast neutrons with hydrogen and nitrogen in tissue is the main cause of biological injury by neutrons.)

Neutrons in the slow and moderate speed ranges can produce ionization indirectly in other ways. When such neutrons are captured by the lighter isotope of boron (boron-10), two electrically charged particles, a helium nucleus (alpha particle) and a lithium nucleus of high energy are formed. Both of these particles can produce ion pairs. Indirect ionization by neutrons can

also result from fission of plutonium or uranium isotopes. The fission fragments are electrically charged particles (nuclei) of high energy which leave considerable ionization in their paths.

9-14 NUCLEAR RADIATION EFFECTS

Nuclear radiation produces ionization in substances exposed to it. With the exception of photographic film, most inanimate materials are unaffected by the ionization produced by nuclear radiation. Living tissue, however, may be destroyed by it. The damage done to an individual by nuclear radiation is dependent on the amount of radiation received (the dose) and the time during which the dose is received. Doses of radiation received from immediate nuclear radiation are called acute doses. Doses received over a period of 12 hours have the same biological effect as doses received all at once and are also acute doses. Doses of radiation received over periods of time longer than 12 hours are called chronic doses. The effects of chronic radiation doses are somewhat different from acute doses. Acute radiation doses are the more important from a tactical point of view. Radiation doses are expressed in terms of a unit called the roentgen. To give an idea of its value, the average dental X-ray delivers five roentgens to the patient's jaw, but only five thousandths of a roentgen of stray radiation to more remote parts of the body. Bodily damage resulting from radiation depends in part on the volume of the body exposed. However, from atomic weapons, the characteristics of the radiation are such that very often the whole body receives the radiation. Doses of interest are, therefore, described as acute whole body doses.

Individuals receiving high acute whole body doses of radiation develop initial symptoms of radiation sickness shortly after exposure. The time of appearance of these initial symptoms varies with the dose; the higher the dose, the sooner the symptoms appear. Initial radiation sickness symptoms are nausea and vomiting which, if the dose is high enough, may be severe enough to make an individual noneffective. The initial symptoms of radiation sickness may disappear after a few hours, depending on the dose received, and there is an apparent recovery. After a period of from a few days to two weeks, called the latent period, radiation sickness symptoms reappear with increasing severity. This second period varies from a few weeks to several months. Death may occur during this period. Table 9-3 shows the effects of various acute whole body doses.

TABLE 9-3 EFFECTS OF ACUTE WHOLE BODY DOSES

Acute Dose	Effects
5000 r	5000 r produce immediate and persistent noneffectiveness until death.
1000 r	Initial sickness appears in 1 hour or less. No survivors are expected.
650 r	Initial sickness appears in all personnel within 4 hours and lasts for about 1 day. Death ensues in about 2 weeks in about 95% of the cases. Survivors are noneffective for 6 months.
450 r	Initial sickness appears in all personnel during first day. About 50% deaths can be expected but this may be reduced by adequate medical treatment. Survivors are noneffective for 6 months.
300 r	Initial sickness during first day in all personnel. About 25% deaths may be anticipated but this may be reduced by adequate medical treatment. Survivors are noneffective for 3 months.
200 r	Initial sickness during first day in about 50% of personnel. Second period of sickness appears after about 3 weeks and lasts for 1 or 2 weeks. No deaths anticipated unless recovery is complicated by poor health, other injury, or infection.
100 r	Initial sickness in about 2% of personnel. All are able to perform duty.

9-15 RESIDUAL RADIATION

Residual nuclear radiation, as distinguished from instantaneous, is defined as that which is emitted later than one minute after detonation. Residual radiation is predominantly gamma. Alpha and beta particles may also be emitted but their importance is negligible if even the simplest precautions are taken against residual gamma radiation. The atomic cloud is highly radioactive and may be a hazard to aircraft crews until it is dispersed. The most significant residual radiation from the point of view of tactical use of atomic weapons is that which persists in the target area.

Fission products constitute a very complex mixture of some 200 different forms (isotopes) of 35 elements. Most of these isotopes are radioactive, decaying by the emission of beta particles, and frequently accompanied by gamma radiation. About 1¾ ounces (0.11 pound) of fission products are formed for each kiloton (or 110 pounds per megaton) of fission energy yield. The total radioactivity of the fission products initially is extremely large, but it falls off at a fairly rapid rate as the result of decay.

At one minute after a nuclear explosion, when the residual nuclear radiation has been postulated as beginning, the radioactivity from the 1¾ ounces of fission products, from a one-kiloton explosion, is comparable with that of a hundred thousand tons of radium. It is seen, therefore, that for explosions in the megaton energy range the amount of radioactivity produced is enormous. Even though there is a decrease from the one-minute value by a factor of over 6000 by the end of a day, the radiation intensity may still be large.

9-16 NEUTRON INDUCED ACTIVITY

The neutrons liberated in the fission process, but which are not involved in the propagation of the fission chain, are ultimately captured by the bomb materials through which they must pass before they can escape; nitrogen (especially) and oxygen in the atmosphere, and various elements present in the earth's surface. As a result of capturing neutrons many substances become radioactive. They, consequently, emit beta particles, frequently accompanied by gamma radiation, over an extended period of time following the explosion. Such neutron-induced activity, therefore, is part of the residual nuclear radiation.

The activity induced in the bomb materials is highly variable, since it is greatly dependent upon the design or structural characteristics of the weapon. Any radioactive isotopes produced by neutron capture in the bomb residues will remain associated with the fission products.

When neutrons are captured by oxygen and nitrogen nuclei present in the atmosphere, the resulting activity is of little or no significance as far as the residual radiation is concerned. Oxygen, for example, interacts to a slight extent with fast neutrons, but the product, an isotope of nitrogen, has a half life of only seven seconds. It will thus undergo almost complete decay within a minute or two. The radioactive product of neutron capture by nitrogen is carbon-14; this emits beta particles of relatively low energy but no gamma rays. Nuclear explosions cannot add appreciably to the fairly large amount of this isotope already present in nature, and so the radiations from carbon-14 are a negligible hazard.

An important contribution to the residual nuclear radiation can arise from the activity induced by neutron capture in certain elements in the soil. The one which probably deserves most attention is sodium. Although this is present only to a small extent in average soils, the amount of radioactive sodium-24 formed by neutron capture can be appreciable. This isotope has a half life of 14.8 hours and emits both beta particles, and, more important, gamma rays of relatively high energy. In each act of decay of sodium-24, there are produced two gamma ray photons, with energies of 1.4 and 2.8 Mev, respectively. The mean energy per photon from fission products is 0.7 Mev, although gamma rays of higher energy are emitted in the early stages.

Another source of induced activity is manganese which, being an element essential for plant growth, is found in most soils even though in small proportions. As a result of neutron capture,

the radioisotope manganese-56, with a half life of 2.6 hours, is formed. Upon decay, it gives off several gamma rays of high energy in addition to beta particles. Because its half life is less than that of sodium-24, the manganese-56 loses its activity rapidly. But, within the first few hours after an explosion, the manganese may constitute a serious hazard, greater than that of sodium.

A major constituent of soil is silicon, and neutron capture by silicon leads to the formation of radioactive silicon-31. This isotope, with a half life of 2.6 hours, gives off beta particles, but gamma rays are emitted in not more than about 0.07 percent of the disintegrations. It will be seen later that only in certain circumstances do beta particles themselves constitute a serious radiation hazard. Aluminum, another common constituent of soil, can form the radioisotope aluminum-28, with a half life of only 2.3 minutes. Although isotopes such as this, with short half lives, contribute greatly to the high initial activity, very little remains within an hour after the nuclear explosion.

When neutrons are captured by the hydrogen nuclei in water, the product is the nonradioactive (stable) isotope, deuterium, so that there is no resulting activity. As seen above, the activity induced in oxygen can be ignored because of the very short half life of the product. However, substances dissolved in the water, especially salt (sodium chloride) in sea water, can be sources of considerable induced activity. The sodium produces sodium-24, as already mentioned, and the chlorine yields chlorine-38 which emits both beta particles and high-energy gamma rays. However, the half life of chlorine-38 is only 37 minutes, so that within 4 to 5 hours its activity will have decayed to about one percent of its initial value.

Apart from the interaction of neutrons with elements present in soil and water, the neutrons from a nuclear explosion may be captured by other nuclei, such as those contained in structural and other materials. Among the metals, the chief sources of induced radioactivity are probably zinc, copper, and manganese, the latter being a constituent of many steels and, to a lesser extent, iron. Wood and clothing are unlikely to develop appreciable activity as a result of neutron capture, but glass could become radioactive because of the large proportions of sodium and silicon. Foodstuffs can acquire induced activity, mainly as a result of neutron capture by sodium. However, at such distances from a nuclear explosion and under such conditions that this activity would be significant, the food would probably not be fit for consumption for other reasons, i.e., blast and fire damage. Some elements, i.e., boron, absorb neutrons without becoming radioactive, and their presence will tend to decrease the induced activity.

9-17 FALLOUT

The tremendous heat resulting from the detonation of a nuclear device in the atmosphere produces a lighter-than-air bubble of intensely hot gases which serves not only to carry aloft the debris resulting from the fissions and the disintegration of the bomb casing and auxiliary equipment, but also to suck up great amounts of soil and dust, much of which is rendered radioactive. As the gases rise, they cool by radiation, by adiabatic expansion, and by entrainment of the surrounding air. The resulting atomic cloud apparently consists of an ascending toroidal ring with debris, dirt, and water droplets circulating about this ring, upward in the center and downward at the outer edges. For relatively low air bursts, the surface material, as a result of the effects of thermal radiation and blast, rises as a column of dust pulled up by the central updraft. The ascending mass of air and debris continues to rise until it has cooled to equilibrium with its environment and lost its upward velocity, usually within six to eight minutes.

Typically, just after the ascending motion has ceased, the cloud of radioactive debris consists of a long, slender stem, capped by a broader mushroom top. Often, especially in the case of low air bursts, the stem and top are not joined (Figure 9-1). Although considerable debris is contained in the stem, the subsequent history of the debris depends on many factors, including the size distribution and fall velocity of the particles; the nature of the wind field; the eddy diffusivity; and

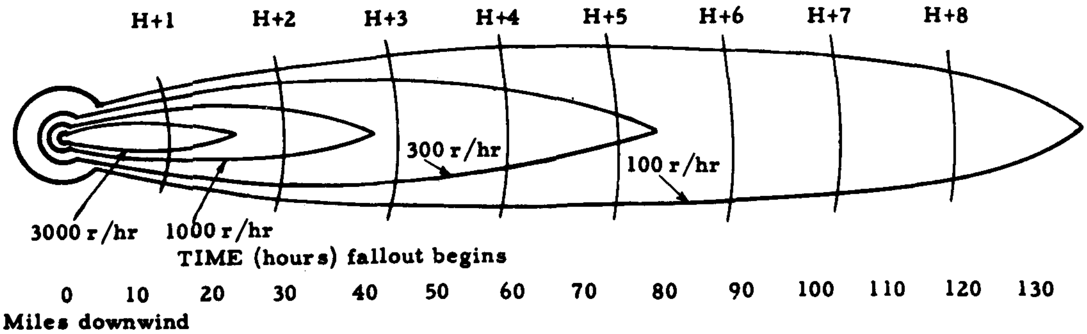

Fig. 9-4 Fallout from a high yield surface burst weapon. Note: Based on 15 knot scaling wind dose rates normalized to one hour after detonation.

the scavenging of particles by precipitation.

The problem of fallout of radioactive particles resulting from atomic explosions divides itself into two major categories: (1) fallout in the vicinity of the burst site (close-in fallout); and (2) distant fallout, that which occurs beyond about 200 miles.

The term fallout refers to the deposition on or near the surface of the earth, of radioactive particles resulting from the detonation of a nuclear device. It includes deposition due to the direct gravitational fall, deposition resulting from vertical currents and eddies in the atmosphere, and to particles scavenged from the atmosphere and deposited by falling precipitation. The latter phenomenon is referred to as rainout.

The movement of the atomic cloud is governed by the wind field. At any given level the trajectory of the primary cloud, (i.e., that portion of the initial cloud which moves approximately horizontally with the winds and is unaffected by diffusion or fallout) may be partially predicted by conventional meteorological techniques. The determination of the movement of all the debris is a much more complex problem. It is, of course, apparent that all of the particles will eventually fall; the larger particles will reach the ground soon after the burst while the smallest may remain airborne almost indefinitely. Knowledge of the size distribution and fall velocity of the particles is so incomplete that only qualitative estimates are available. Horizontal and vertical wind shears coupled with fallout and diffusion can result in a very rapid spreading of the cloud in many instances. In other cases, where mixing is inhibited by stable stratification or little wind shear exists, relatively concentrated patches of debris can be carried for long distances in the upper troposphere.

The size and shape of the area contaminated by fallout is governed by the yield of the weapon, the height to which the cloud ascends, and the strength and direction of the winds at various altitudes. Figure 9-4 shows the fallout pattern that can be expected to result from a high yield weapon detonated on the surface.

Fallout intensities decay rapidly for the first few hours; after six hours the rate of decay is much slower. Table 9-4 shows, for various times after detonation, the fraction of the dose rate at one hour to which fallout decays.

TABLE 9-4 DECAY FACTORS FOR FALLOUT

Time After Detonation in Hours	Fraction of Dose Rate at 1 Hour
1	1.00
1.5	0.62
2	0.44
4	0.19
6	0.11
8	0.08
10	0.06
12	0.05

9-18 LONG-TERM RESIDUAL RADIATION HAZARD

Of the fission products which present a potential long-term hazard from either the testing of nuclear weapons in peacetime or their use in warfare, the most important are probably the radioactive isotopes cesium-137 and strontium-90. Since both of these isotopes are fairly abundant among the fission products and have relatively long half lives, they will constitute a large percentage of any world-wide fallout. Of course, the activity level due to these isotopes at late times in the local fallout pattern from a surface or subsurface burst will be considerably larger than in the world-wide fallout from a given nuclear burst.

Cesium has a radioactive half life of 30 years and is of particular interest in fallout that is more than a year old because it is the principal constituent whose radioactive decay is accompanied by the emission of gamma rays. The gamma rays are actually emitted, within a very short time, by a high-energy state of the decay product, barium-137. The chemical properties of cesium resemble those of potassium. The compounds of these elements are generally more soluble than the corresponding compounds of strontium and calcium; and the details of the transfer of these two pairs of elements from the soil to the human body are quite different. Cesium is a relatively rare element in nature and the body normally contains only small traces. Consequently, the biochemistry of cesium has not been studied as extensively as that of some of the more common elements. It has been determined, however, that cesium-137 distributes itself within living cells in the same way as potassium, so that it is found mostly in muscle. Based on one experiment with several human subjects, the current estimate of the time required for normal biological processes to reduce the amount of cesium in the body by one-half, i.e., the biological half life, is 140 days. Because of the penetrating properties of the gamma rays from the decay of cesium-137, the radiation is distributed more or less uniformly to all parts of the body. Although the radioactive decay of cesium-137 is accompanied by gamma ray emission, the relatively short time of stay, together with most of the cesium being in a less sensitive location in the body, indicates that for the same amount of stratospheric fallout, the residual cesium-137 will be less of a general pathological hazard than the residual strontium-90.

Attention will now be given to what is probably the more serious long-term radiation hazard. Because of its relatively long radioactive half life of 28 years, and its appreciable yield in the fission process, strontium-90 accounts for a considerable fraction of the total activity of fission products which are several years old. Thus, even such material as has been stored in the stratosphere for several years will be found to contain a large percentage of this radioactive species. Strontium is chemically similar to calcium, an element essential to both plant and animal life; a grown human being, for example, contains over two pounds of calcium, mainly in bone. As a consequence of the chemical similarity, strontium entering the body follows a path similar to calcium and therefore is found almost entirely in the skeleton, from which it is eliminated very slowly. Thus, the half life of strontium in human bone is estimated to be about ten years. The probability of serious pathological change in the body of a particular individual, due to the effects of internal radioactive material, depends upon the intensity and energy of the radioactivity and upon the length of time the source remains in the body. Although strontium-90 emits only beta particles (no gamma rays), a sufficient amount of this isotope can produce damage because once it gets into the skeleton it will stay there for a long time. As a result of animal experimentation, it is believed that the pathological effects which may result from damaging quantities of strontium-90 are anemia, bone necrosis, and certain types of cancer, possibly leukemia. It is the combination of physical and chemical properties of strontium-90, namely, its long radioactive half life and its similarity to calcium, together with the nature of the pathological changes which can result from concentrations of radioactive material in the skeleton, that make strontium-90 the most important isotope (so far as is known) as a possible cause of harmful long-term effects of

fallout.

Genetic effects due to strontium-90 are relatively insignificant. In the first place, owing to their very short range in the body, the beta particles from this isotope in the skeleton do not penetrate to the reproductive organs. Further, the intensity of the secondary radiation (bremsstrahlung) produced by the beta particles is low. Finally, the amount of strontium-90 in soft tissue, from which the beta particles might reach the reproductive organs, is small and may be neglected in this regard.

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CHAPTER 10

BALLISTIC ATTACK OF ARMOR USING KINETIC AND CHEMICAL ENERGY EFFECTS

10-1 GENERAL

A specialized field of terminal ballistics and one in which new developments are of critical importance concerns consideration of the means available to accomplish defeat of protected targets, primarily armor and concrete. These two defensive devices, along with the bunker-type field fortifications that were so effective in battles throughout the Pacific regions in World War II and the Korean War, frequently require special techniques for attack. Included in the types of weapons suitable for attacking such targets are napalm or fire bombs which are a tremendously effective psychological weapon and one which threatens personnel with fire and suffocation. These weapons however, are not of the highly specialized variety as are kinetic or chemical energy type rounds.

Successful attack of any target is dependent upon the characteristics of the target itself, hence this phase of terminal ballistics is divided into two parts: Chapter 10 for the study of the defeat of armor; and Annex B to Part 2, the defeat of concrete. Both the offensive and defensive aspects of both types of material will be considered because both may be in the hands of the attacker and the defender in future combat.

10-2 TYPES OF ARMOR MATERIALS

Armor is generally thought of as being steel, and almost all armor in use is steel. However, research indicates the possibility of aluminum, titanium, and other light metals being used for armor, particularly where weight savings would offset the increased cost of these materials over steel. In addition, certain nonmetals show promise as armor materials, particularly in the role of body armor. The three major applications of steel as armor include:

10-2.1 ROLLED HOMOGENEOUS STEEL ARMOR

For a number of years the most common type of armor used in the construction of combat vehicles has been rolled alloy steel produced and heat-treated so as to give it, as nearly as possible, the same chemical and physical characteristics throughout its structure. Chemically it consists of steel with the following alloying elements added: 0.50—1.25% chromium; 0.5—1.5% nickel; 0.3—0.6% molybdenum; 0.8—1.6% manganese; and 0.30% carbon. It is usually used as plate, furnishing conveniently flat walls on which to base the design of the inside of the vehicle, although it can be bent to a limited extent to form curved surfaces. It is more easily produced in large quantities than either face-hardened or cast homogeneous steel and can be welded into a vehicle structure with little difficulty. It has high toughness and ductility and affords the best protection against the shock of impact of relatively large caliber projectiles as well as the blasts of high explosive missiles. The bow armor of the armored infantry vehicle (Figure 10-1) is an example of rolled homogeneous armor.

10-2.2 CAST HOMOGENEOUS STEEL ARMOR

Chemically, cast homogeneous armor is virtually the same as rolled homogeneous armor. It is given its shape by casting in a mold and receives its optimum ballistic properties by subsequent heat treatment. The advantage of cast armor is that it can be molded into almost any shape,

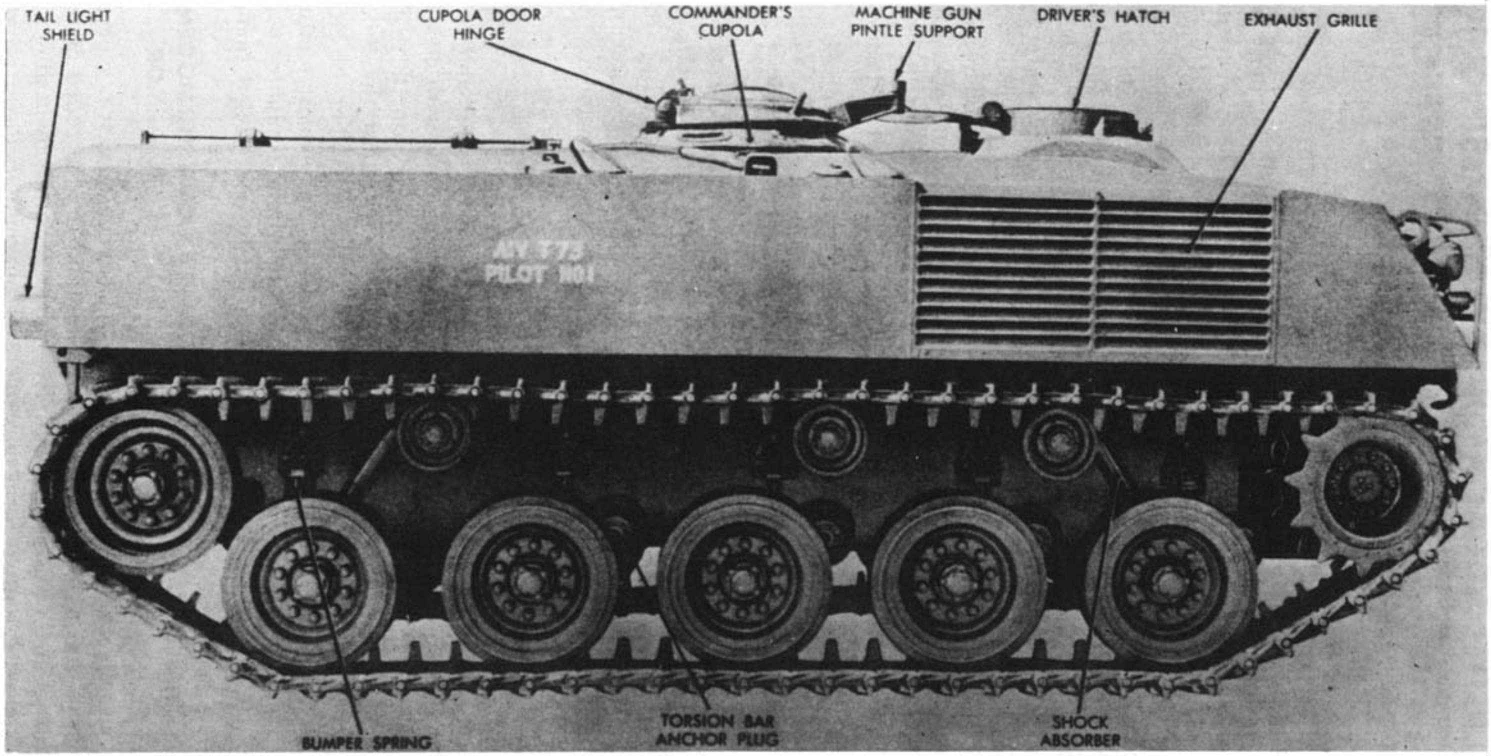


Fig.10-1 Armored infantry vehicle, right side view.

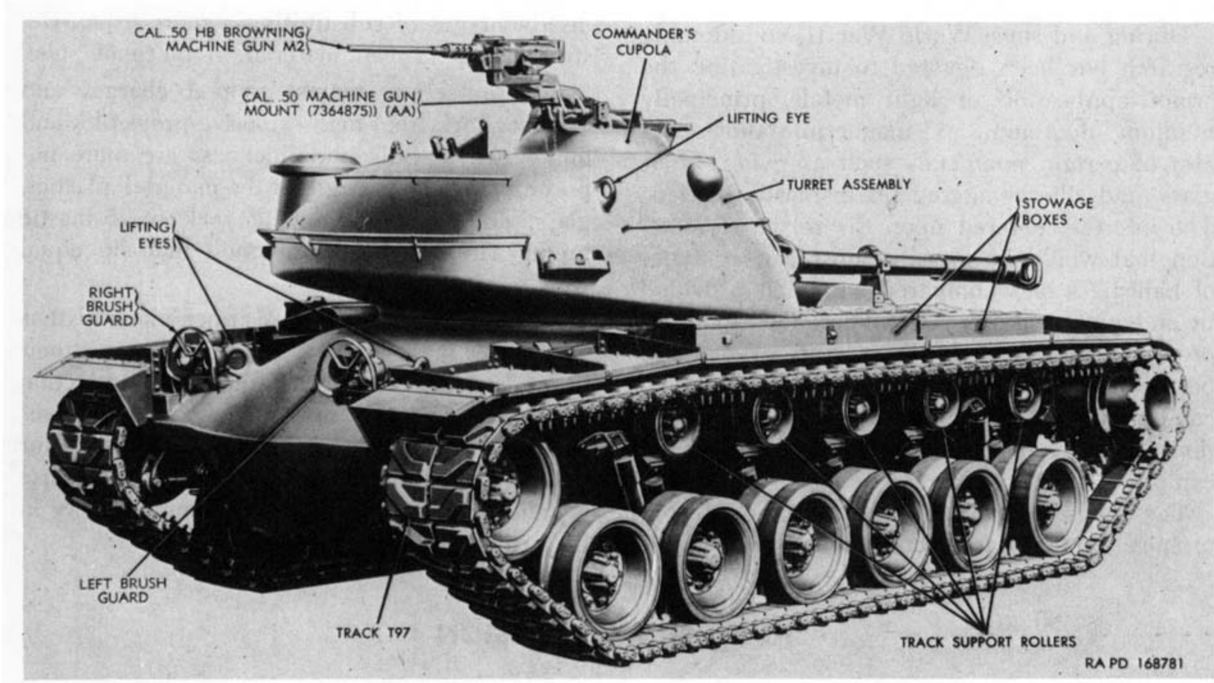


Fig. 10-2 90-mm gun tank, M48.

furnishing curved surfaces of any desired thickness. The high convexity possible with cast armor is illustrated in Figure 10-2. The oval shaped turret and elliptically shaped hull of this vehicle are both single, homogeneous steel armor castings. On the other hand, since the effect of heat treatment depends upon the thickness of the cast section, it is more difficult from a manufacturing viewpoint to obtain the proper ballistic properties in castings since they have great variations in thickness. Also, castings cannot be hot-worked (a process which refines grain structures and eliminates casting cavities); therefore they are not as tough and shock-resistant as rolled armor. In general, rolled armor is about 15% better in resistance to shock and penetration than cast armor. However, this advantage is offset to some extent by the varying angles of obliquity and irregular shapes possible in castings. These variations in shape considerably decrease the penetrating ability of certain types of projectiles.

In vehicle design it may be practical and desirable to use a combination of homogeneous plate and castings which can be joined by welding into the finished form. The M48 tank has a floor of rolled flat plate welded to a cast hull.

10-2.3 FACE-HARDENED STEEL ARMOR

Face-hardened armor is characterized by an extremely hard outer face with a relatively soft, tough back. It is usually manufactured from rolled homogeneous plate by a surface carburizing process. The advantage of using face-hardened armor lies in its ability to shatter projectiles striking its hard surface, thereby greatly reducing their ability to penetrate. Face-hardened armor has very limited shock resistance due to its brittleness resulting from high hardness. It is more difficult to manufacture than homogeneous armor, since carburizing necessitates heating in a furnace for a considerable period of time. It is also difficult to weld because of its high surface carbon content, very often cracking in welding or afterwards from residual stresses set up within the plate. Because of these difficulties, face-hardened plate is rather expensive and cannot be manufactured or fabricated in tonnages comparable to homogeneous plate. Its principal application is for protection of personnel against small arms fire and its use as gun shields on mobile guns and on armored personnel carriers (Figure 10-1).

10-2.4 NONFERROUS ARMOR MATERIALS

During and since World War II, considerable research has been devoted to investigating the armor application of light metals, principally titanium, aluminum, and magnesium alloys, and also of certain nonmetals such as nylon, fiberglass, and silicate aggregates in mastic binders. The interest centered upon the relative protection that would be given against various types of ballistic attack compared with that provided by an equal weight of steel. These investigations proved definitely, that for weights of material permissible in body armor, steel is inferior to combinations of aluminum and nylon for protection against small caliber bullets and high explosive shell fragments.

The alloys of certain light metals show future promise for use as aircraft armor where the importance of weight saved would offset the disadvantages of substituting a more expensive, strategically critical material in place of steel.

For protection against shaped charges and against shock from high explosive projectiles and mines, where bulk and thickness are more important than the strength of the material, plastics, glass, and ordinary silicate rock in a mastic binder offers greater protection than an equal weight of steel.

None of these nonferrous armor materials has yet come into general usage; however, their future is assured by the improved protection which is provided, on an equal weight basis, against certain types of attack. The search for lighter armor materials is continuous, because weight is one of the most important factors in the use of armor.

10-3 SURFACE DESIGN

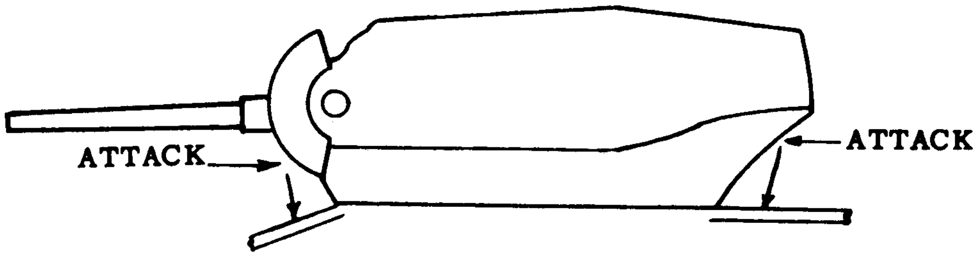
In addition to providing the maximum advantage of obliquity, the apportionment of protection in accordance with the expected severity and directions of attack, and the uniformity of protection from any one direction of attack, the optimum design in an armor structure will also provide for an overall convex surface. This requires avoiding re-entrant angles and irregularities such as joints between sections, sudden changes in thickness, sudden changes in obliquity, installed components, and attachments welded to either the inside or outside surface of the armor.

A flat or a convex surface tends to reject impacts at obliquities and is by far preferable to a concave surface containing a re-entrant angle (Figure 10-3) which tends to catch attacking projectiles, thereby increasing the dangers of ricochet and bullet splash. The latter condition often causes an attacking projecile to be turned against a surface which provides less protection and which in most cases would not be exposed to attack. Moreover, re-entrant angles often cause a thinner wall section not exposed to direct attack to suffer penetration when attacked by the blast of a high explosive projecile.

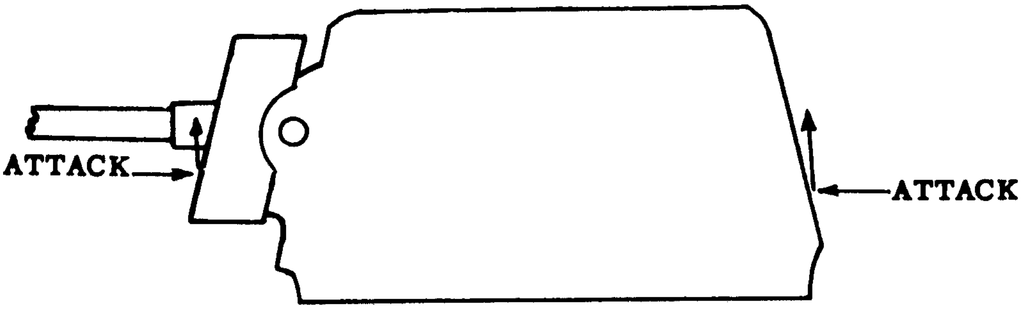
Surface irregularities, either inside or outside the vehicle, tend to create weaknesses in the armor and therefore should be avoided. A flat, smooth wall of constant thickness offers the best resistance to severe attack, principally because the shock of impact can be uniformly absorbed over the entire area. Any irregularity, whether it be a reinforcing brace, a protective bead, a sudden change in thickness, a sudden change in obliquity, or a welded joint, tends to restrict uniform deformation and may set up, near the irregularity, stress concentration of sufficient magnitude to cause failure.

10-4 FABRICATION OF MOBILE ARMOR STRUCTURES

Almost all fabrication of structures of homogeneous armor (and therefore, the greatest percentage of all armor fabrication) is accomplished by arc welding. Since flying boltheads, nuts, and rivetheads (detached from the inside wall of the tank when the armor is struck on the outside) constitute a hazard to the crew and to equipment within the tank, and since welded joints in homogeneous armor can be made ballistically stronger than either bolted or riveted joints, whenever



TURRET WITH REENTRANT ANGLES



TURRET WITHOUT REENTRANT ANGLES

Fig. 10-3 Reentrant angle effect.

practicable, bolts and rivets have been abandoned in favor of arc welding, which produces a joint far superior in ballistic strength to any other method of welding.

In the fabrication of structures employing face-hardened armor, the heat developed during the arc welding operation affects the hardened face of the armor, causing it to become more brittle in the region adjacent to the weld and thus making it less resistant to both penetration and shock in the vicinity of the joint. For this reason other methods of fabrication which afford greater ballistic strength may be preferable, despite their disadvantages. Methods in general use are: arc welding, bolting, riveting. It is of interest to note that an attempt has been made to increase the ballistic strength of a welded face-hardened armor joint by masking the edges of the plate during the face-hardening process so that the finished plates have edges of homogeneous armor. This practice, however, may result in considerably lowering the resistance to penetration of the masked area as compared to that of the basic face-hardened armor.

The principal requirement of an armor joint, insofar as its ballistic properties are concerned, is its resistance to shock. In order to prevent general rupturing of the armor structure when the vehicle is struck by an attacking projectile, the joints between the armor plates and/or casting should be of such design, and of such ballistic strength, that they will withstand as severe a shock test as the basic armor without permitting the plates and/or castings to separate. The welding procedure to be used for any particular joint should be selected on the basis of its inherent ability to provide the maximum resistance to both shock and penetration in all areas affected by the welding.

10-5 INNOVATIONS

All during its history, armor has been unable to keep pace with improvements in armor attacking weapons. In almost every period marked by military progress, new developments in arms and

ammunition have created additional difficulties even before satisfactory solutions to old and existing armor problems had been found. Because this situation is particularly true today, the question arises as to what changes in armor might be made in an effort to defeat, or at least reduce, the destructive effect of modern projectiles.

10-5.1 SPACED ARMOR

Apart from the development of new materials, further consideration of the question suggests that a solution to the problem may result either through the use of spaced armor or through some new development in composite armor. While experience indicates that the latter approach offers little or no chance of success, there is always a possibility that the discovery of new materials and methods may change the picture sufficiently to permit a solution. During World War II the Germans used spaced armor to a limited extent. Whether or not it can be advantageously used in the future depends upon further investigation and development. Spaced armor consists of two or more plates located at relatively great distances from each other. In order to defeat armor piercing projectiles, the initial plate must either break up the attacking projectile or turn it sufficiently from its trajectory to prevent penetration. In order to defeat hollow charge projectiles, the initial plate must be able to withstand the attendant forces so that the energy released will be adequately dissipated before a secondary plate can be attacked. Alternate protective concepts include the use of externally mounted spikes to spoil stand off distance of incoming rounds; detonation of small shaped changes against the jet of the attacking rounds; resilient screens; and coatings of violently oxidizing material to cause disposal of the jet. Any investigations which may be conducted must include such factors as silhouette, method of support, weight, jettisoning, and mobility.

10-5.2 LAMINATED ARMOR

Laminated armor of layer-upon-layer of steel is basically inferior to a single piece of armor of the same overall thickness. This phenomenon has been verified by repeated test firings with little hope existing for increased ballistic performance of armor through the use of laminated plate.

10-5.3 COMPOSITE ARMOR

Since World War II considerable experimentation has been conducted to establish data pertinent to the terminal effects of various kinetic energy, H.E., A.T., and H.E.P. rounds on armor in use or in the development stage. One should consider the possible future utilization of nonferrous metals and steel plate by the intimate bonding of two or more of them into a composite form providing the maximum possible protection against all types of rounds, with the composite armor affording better protection per unit of weight than steel. This opens the door for composite armor of aluminum or magnesium alloys affording as much protection as steel for shock and penetration of kinetic energy rounds; silicate aggregates in mastic binders affording protection from H.E. and A.T. rounds; and resilient materials for shock action. Combinations of materials in a composite form obviously will require great strides in fabrication techniques as well as increased performance over that presently possible. However, with continued technological advancements, the future may well see the fabrication of composite armor as a partial answer at least in the search for maximum protection against the multiplicity of rounds currently available.

10-6 NECESSARY BALLISTIC PROPERTIES OF ARMOR

The necessary ballistic properties which are required of armor consist of resistance to penetration, resistance to shock, and resistance to spalling.

10-6.1 RESISTANCE TO PENETRATION

Resistance to penetration is that property which prevents a projectile from passing partially or entirely through armor plate. When penetration occurs, either a cylindrical plug is driven from the back of the plate or the metal is pushed aside, some of it flowing towards the exposed face where it forms a lip, and the remainder being pushed towards the unexposed surface (back) forming a convex protrusion which may be expelled in one piece or as scattered fragments (Figure 10-4).

10-6.2 RESISTANCE TO SHOCK

Resistance to shock is that property which permits armor to absorb, without cracking or rupturing, the energy expended against it by either an attacking projectile of relatively large caliber, or the explosion of a high explosive projectile. Because of the very high velocities at which projectiles strike and at which high order explosions take place, this energy must be absorbed in an extremely short period of time. Low temperature decreases the shock resistance of armor by making it more brittle and thus less able to absorb the shock (Figure 10-5).

10-6.3 RESISTANCE TO SPALLING

Resistance to spalling is that property which tends to resist cracking, flaking, or breaking away of the armor plate, particularly on the inner surface opposite the point of impact. In general, where spalling occurs, the diameter of the opening on the rear surface of the plate is considerably greater than the caliber of the projectile which caused penetration. In substance, resistance to spalling is a measure of the soundness of the steel and the quality of its heat treatment (Figure 10-6).

The three physical properties in armor which have the greatest influence on its ballistic properties are:

(a) Hardness: the ability of the armor to resist indentation.

(b) Toughness: the ability of the armor to absorb energy before fracturing.

(c) Soundness: the absence of local flaws, cavities, or weaknesses in the armor. Unsoundness is not so often found in rolled armor as in cast armor, because of the mechanical working which has been done during the hot-rolling process.

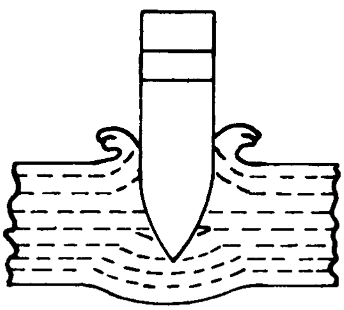
10-7 EFFECTS OF OBLIQUITY AND HARDNESS ON PERFORMANCE OF ARMOR

The ballistic properties of armor depend upon several factors: the type and thickness of the armor; the ratio of the thickness of the armor to the caliber of the projectile (T/D ratio); the type of projectile; the striking velocity; the obliquity of impact; and the hardness of the armor.

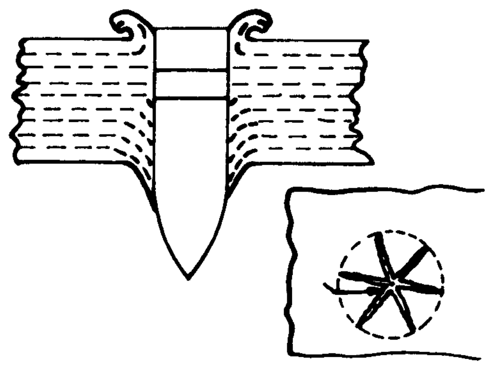
The ratio between the armor thickness (T) and the diameter of the projectile (D) is expressed as the T/D ratio. If T/D is greater than 1, the projectile is said to be undermatching in relationship to armor thickness; if T/D is equal to 1, the projectile is said to be matching; and if T/D is less than 1, the projectile is overmatching. When T/D ratio is varied, there is considerable difference in the displacement of metal as the projectile pushes through the plate. The performance of different caliber projectiles is roughly comparable when the T/D ratio remains constant.

10-7.1 EFFECT OF OBLIQUITY UPON RESISTANCE TO PENETRATION

When the obliquity of impact against a given thickness of armor is increased, resistance to penetration is also increased. Basically, little or no change in resistance to penetration occurs as the obliquity begins increasing from 0° until somewhere in a range of from 10° to 20° the curves begin to rise more and more rapidly. The sharp rise is attributable to the failure (fracture or shatter) of the projectile thereby increasing resistance to penetration. The location of the beginning of the rapid rise and the steepness of the curve at any particular obliquity depend upon several factors already mentioned: the T/D ratio, the hardness of the armor, and the type of projectile. In general, high obliquity impact causes

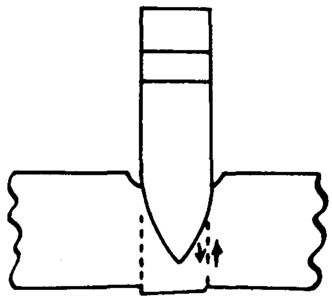


Formation of bulge.



Formation of petalling on back and front of plate.

Fig. 10-4 Formation of petalling and plugging as a result of penetration. (Sheet 1 of 2.)



Formation of plugging.

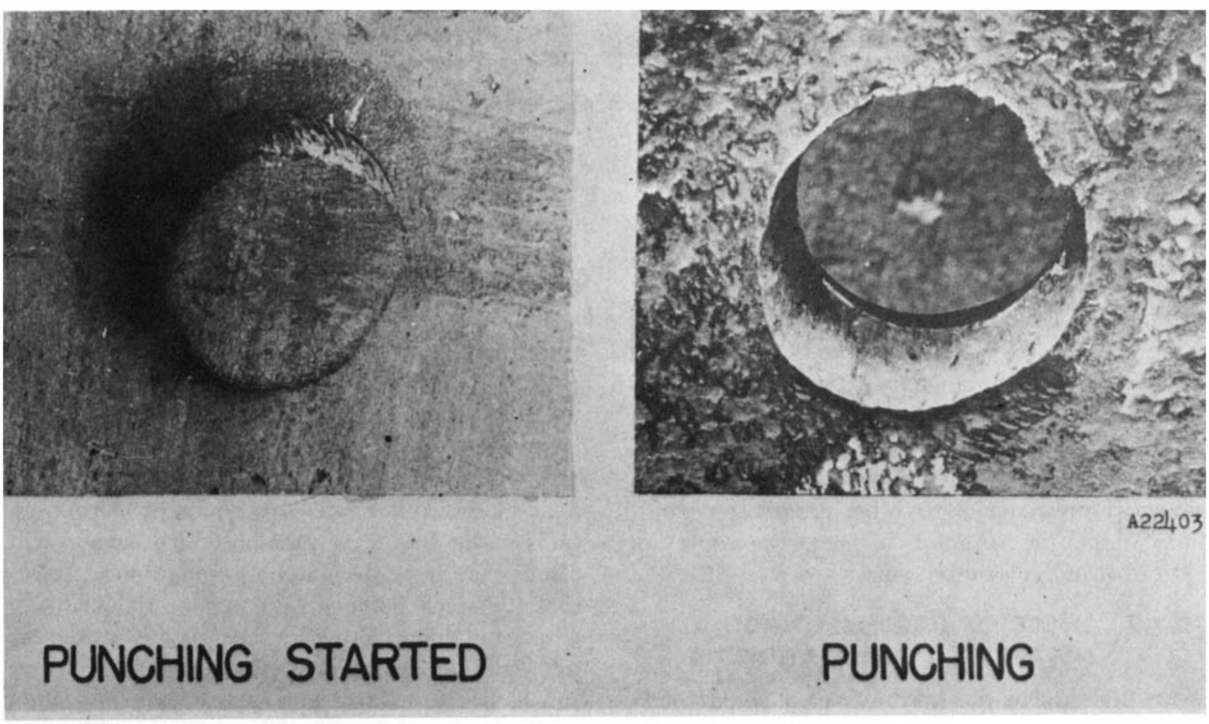


Fig. 10-4 Formation of petalling and plugging as a result of penetration. (Sheet 2 of 2.)

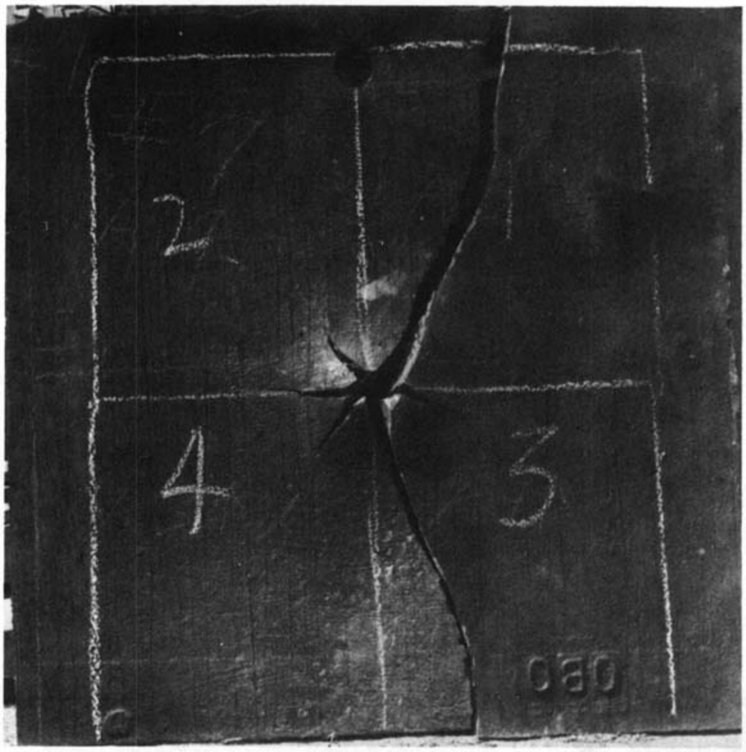


Fig. 10-5 Failure of a 1½-inch cast armor plate resulting from shock of impact during low temperature tests.

a projectile either to ricochet or to shatter, thereby greatly reducing its ability to penetrate. In addition, if the projectile does penetrate, it must displace a greater volume of metal to perforate armor on an oblique path rather than taking the shortest path through; that is, a path normal to the surface. Thus a piece of armor plate 2 in. thick, sloped at 55°, may afford as much protection as a piece of armor plate 5 in. thick with no slope. Interior space and other design considerations limit the amount of slope possible on various armored components.

10-7.2 EFFECT OF HARDNESS UPON RESISTANCE TO PENETRATION

An increase in the hardness of a given thickness of armor may result in an increase, in a decrease, or in no change at all in resistance to penetration depending upon the T/D ratio. Where undermatching projectiles are concerned, resistance to penetration at normal impact increases as hardness increases; where overmatching projectiles are concerned, resistance to penetration at normal impact decreases as hardness increases; and where matching projectiles are concerned, little change in resistance to penetration at normal impact occurs over a considerable range in hardness. These relationships are illustrated in Figure 10-7, wherein an undermatching (20-mm) projectile, a matching (37-mm) projectile, and an overmatching (57-mm) projectile have been fired against various hardnesses of armor one and one-half inches (38-mm) in thickness. These differences are generally accounted for by the fact that face-hardened armor will often shatter undermatching monobloc projectiles, whereas homogeneous armor is less likely to shatter them. However, due to the brittleness inherent with hardness, face-hardened armor shows poorer elastic and plastic response than homogeneous armor, and hence is less likely to resist penetration of an intact projectile. A most important factor in selecting the hardness desired in a particular piece of armor is the caliber of projectile that the armor must withstand. Lightly armored vehicles such as personnel carriers and self-propelled artillery generally employ face-hardened armor since they can only hope to

withstand small arms fire and shell fragments which would be undermatching.

No mathematical relationship has yet been established to link the effects of obliquity and hardness upon resistance to penetration, for no two sets of conditions among type and thickness of armor and type and model of projectile necessarily produce exactly the same result; therefore, Figure 10-7 cannot be given general application. The designer of a combat vehicle should establish armor requirements only after a study of a complete tabulation of data for each type and thickness of armor and each caliber and model of projectile to be considered. Due to the magnitude of the effect of increased obliquity upon resistance to penetration, every advantage should be taken of the effect of obliquity in the design of all combat vehicles, gun shields, and other armor structures. Wherever possible, armor surfaces presented to attack by enemy fire should be inclined at the highest obliquities permissible within the limitations of the other design considerations.

10-7.3 DISCUSSION

Since the resistance to shock is a measure of the ability of armor to absorb energy, the obliquity of attack has little effect other than that at high obliquity impact, the armor will absorb less energy in deflecting the projectile into ricochet than if the projectile imbedded itself. However, the hardness of armor has great effect upon its shock resisting properties. Armor of the higher hardnesses tends to be more brittle and to crack under severe shock of impact or blast, while armor of the lower hardnesses tends to be more tough and ductile and to withstand greater shock. But armor of too low hardness cannot provide sufficiently high resistance to penetration or massive deformation, so a compromise is necessary.

The hardness of armor and obliquity of attack have little effect upon resistance to spalling, as spalling is essentially dependent upon the soundness of the steel and the quality of its heat treatment. However, once perforation has been obtained, armor plate of the higher hardnesses will generally spall more (Figure 10-8).

10-8 KINETIC ENERGY PROJECTILES

10-8.1 DEFINITION OF TERMS

(a) Penetration-perforation. In considering the effects of missiles on targets it has been found useful to distinguish between penetration and perforation. The term penetration is reserved for the entry of a missile into the armor without passing through it. The term perforation implies the passage of the missile completely through the armor.

(b) Target. That materiel or personnel whose injury or destruction will nullify or lessen the effectiveness of the enemy. In the specific case of a tank the target may be the crew, ammunition, fuel system, radios, fire control equipment, armament, or structural or moving parts such as the engine, power train, track, etc. The target itself is usually highly vulnerable if its protective armor can be perforated.

(c) Striking velocity. Velocity of the projectile at the instant of impact.

(d) Residual velocity. Velocity of the projectile after perforation.

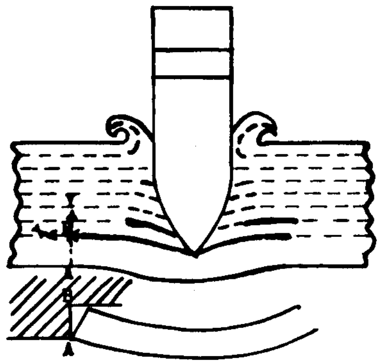
(e) Shatter. The breaking of the projectile into a number of pieces by complex shearing actions rather than by brittle failure.

(f) Shatter velocity. That striking velocity at which the projectile, for a given angle of incidence, will shatter into two or more parts when striking a given type of armor.

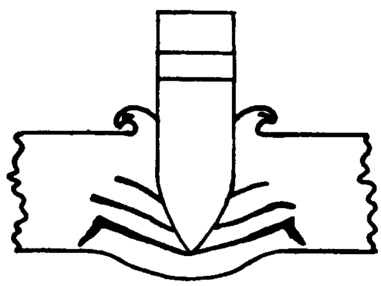
(g) Angle of incidence or striking angle. The angle measured between the normal to the armor at the point of impact, and the tangent to the trajectory at the same point (see Figure 10-9).

(h) Striking energy. The kinetic energy possessed by the projectile at the instant of impact due to its mass and striking velocity. The kinetic energy of rotation of the projectile is usually ignored.

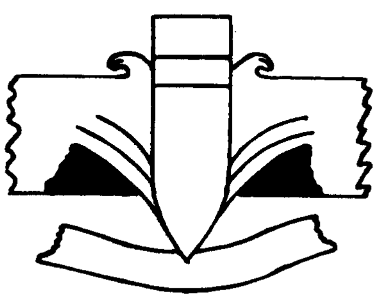
(i) Armor piercing cap. A metal cap affixed to the nose of a projectile in order to increase the velocity at which shatter will occur by decreasing initial impact stress due to inertia.



Tensile and shear stresses in formation of spall

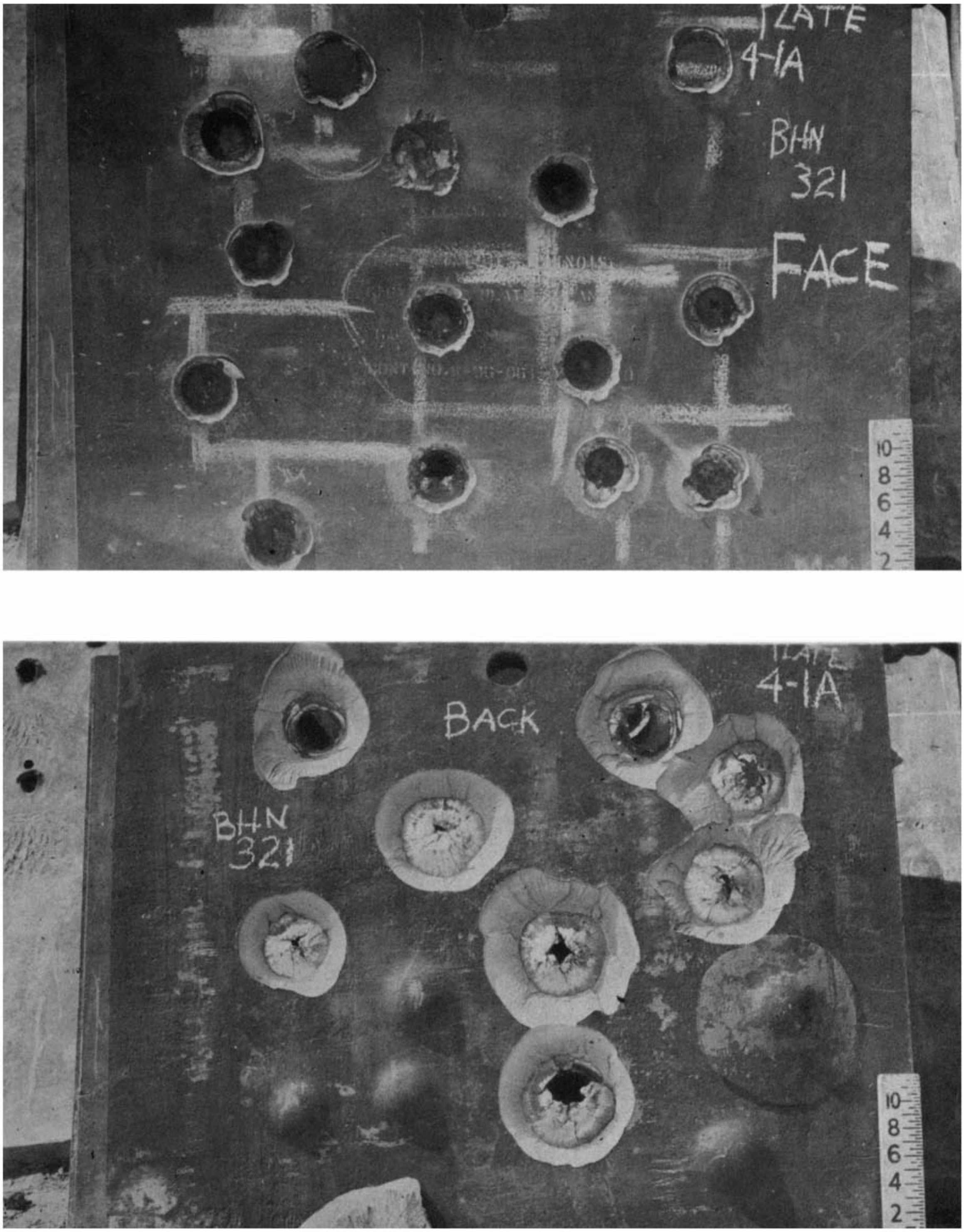


Separation into layers during formation of spall



Spall

Fig. 10-6 Formation of spall in armor. (Sheet 1 of 2.)



Example of displacement of backspall from armor

Fig. 10-6 Formation of spall in armor. (Sheet 2 of 2.)

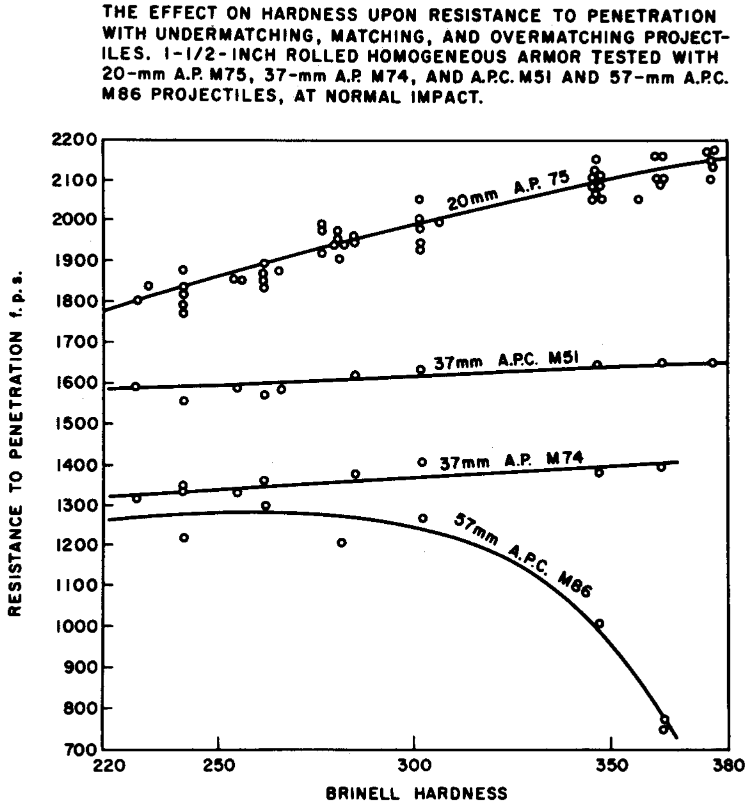


Fig. 10-7 Resistance to penetration versus hardness.

(j) Sub-projectile or core; sabot; composite rigid. The sub-projectile or core is a sub-caliber projectile made of high density, high strength material, e.g., tungsten carbide. The core is usually placed inside a carrier or jacket of low density material, e.g., aluminum. The core is that part of the complete projectile which is intended to perforate the armor. The jacket may be discarded in flight in which case it is called a sabot, or the jacket may remain with the projectile until impact. In the latter case the ammunition is termed composite rigid type.

(k) Ballistic limit. The lowest striking velocity which produces penetration sufficient to crack the inner surface of the plate. (The ballistic limit as defined in naval ordnance terms requires complete perforation, the resulting hole being equal in diameter to projectile size.)

10-9 GENERAL EFFECTS OF IMPACT—PROJECTILE DEFORMATION

The ability of a projectile to destroy a target depends in large part on the relation between the amount of protection possessed by the target and the power of the missile. Competition between strength of protection and missile power is as old as warfare, and this chapter again discusses some of the latest aspects of this competition.

At impact there is a contest between missile and armor in which not only the armor but also the missile may yield in varying degrees. Thus a projectile with high striking energy may shatter against armor or a general purpose bomb may deform or rupture against concrete thereby dissipating energy required for perforation. The energy is dissipated in the sense that a shattered

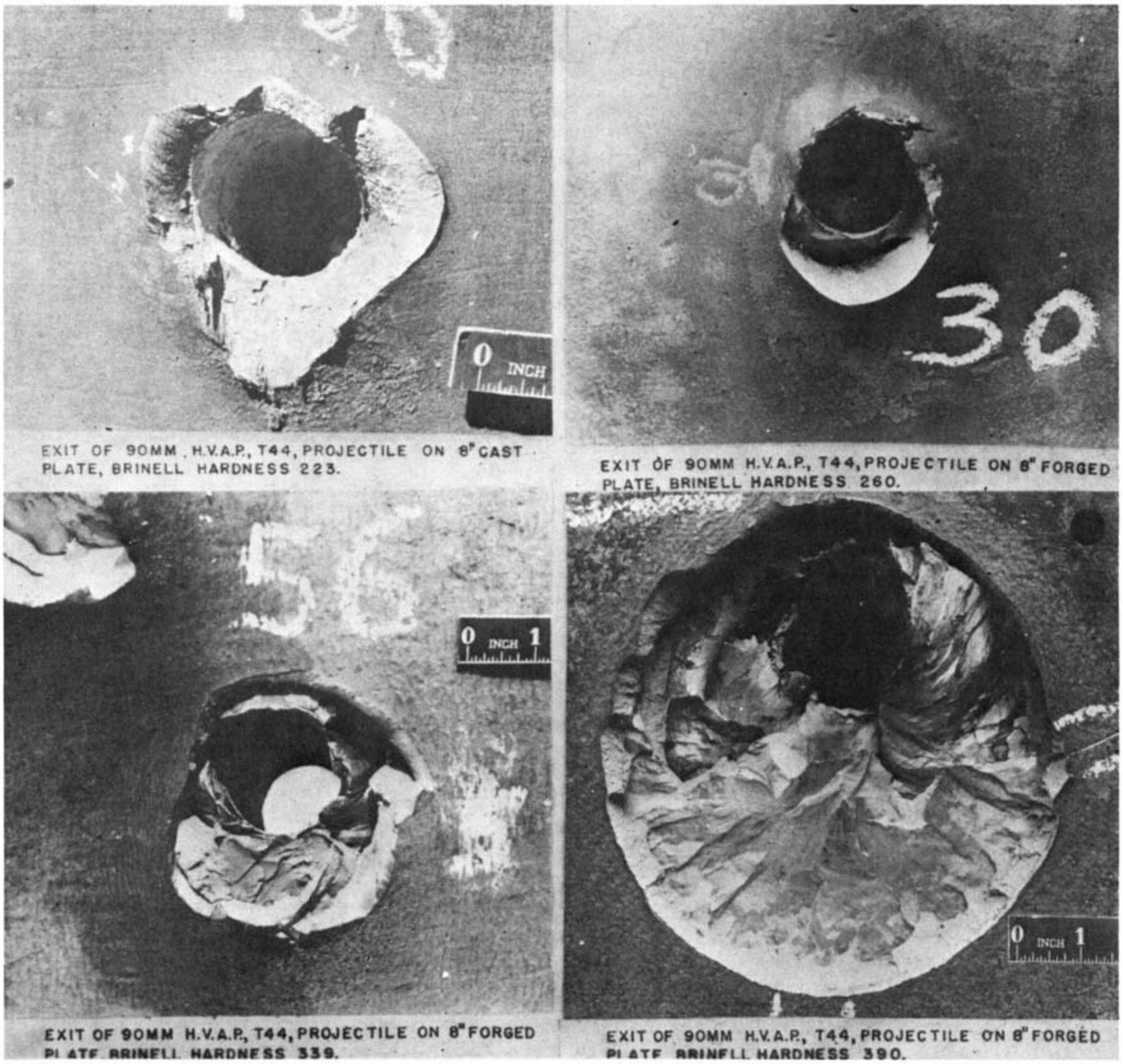


Fig. 10-8 Views of projectile exit regions.

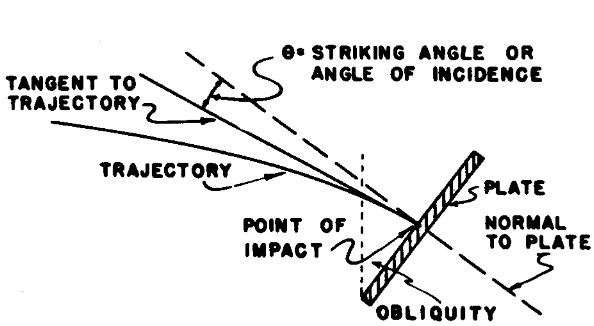


Fig. 10-9 Striking angle or angle of incidence.

projectile spreads out to cover more area and the energy per unit of impact area is lower than it would be for an undeformed projectile. In either case a considerable indentation into the target may be achieved though less than would be produced by a nondeformed missile. If perforation is required it becomes axiomatic that a projectile must remain undeformed during impact if it is to utilize most efficiently its available kinetic energy.

The stresses in a projectile at the time of impact, and therefore its tendency to deform, increase continuously with increase in striking velocity. Although the details of the resultant

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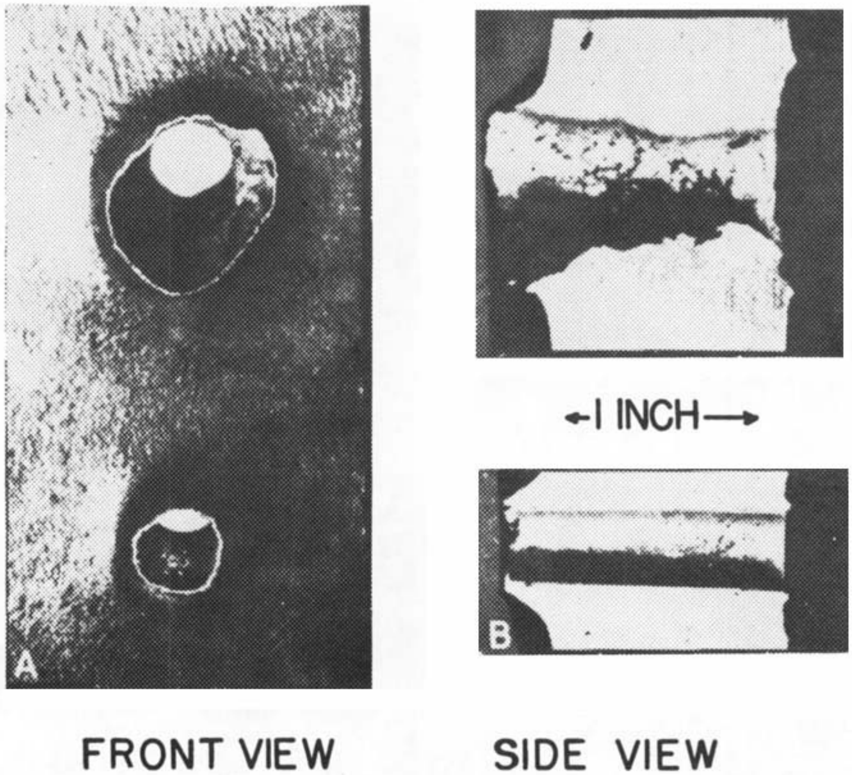

Fig. 10-10 Perforation above shatter velocity (top) and below shatter velocity (bottom).

progressive disintegration change with variations in projectile characteristics, the general pattern is the same for all. On striking the plate at velocities below a certain critical value (whose magnitude depends on the properties of the projectile, the type of armor, and the angle of incidence), the projectile remains intact. As the velocity is increased above this value, the projectile deforms progressively until at a sufficiently high velocity it almost completely disintegrates on impact. At a velocity (really, within a narrow range of velocities) somewhat above the velocity at which the initial projectile failure takes place, the hole made in the plate changes from one of approximate projectile diameter with smooth sides to one that has a rough, jagged surface and is greatly oversize. These two types of holes are shown in Figure 10-10. Concurrently with a change from a small to an oversize hole there is usually an abrupt increase in the energy required for perforation. When the nose of the projectile is in several small pieces an oversize hole is always produced if perforation is achieved at all.

The initial failure may occur either in the nose or in the body of the projectile. If the initial failure takes place in the nose, the direct result is projectile shatter. This occurs with projectiles of convential nose shape at velocities only slightly higher than the body rupture velocity. As the striking angle is changed, the shatter velocity likewise changes. This effect is shown in Figure 10-11. The projectiles pictured were all fired so as to produce a striking velocity of 2000 ft/sec. There is no shatter for striking angle (θ) of 0°. The amount of disintegration increases with an increase in the striking angle. The projectile disintegration also depends upon striking velocity. This fact is illustrated in Figure 10-12. As the velocity is increased the degree of disintegration also increases. These figures illustrate the result of projectile impact on thin plate (⅜ inch). In similar tests for plate of greater thickness, only

APPENDIX A

INSTRUMENTATION

A-1 INTRODUCTION

Instrumentation is the science of gathering and evaluating data derived from testing actual pieces of equipment. As weapons of war have become more expensive and complex, it has become necessary to make instrumentation coverage more complete and exact than was formerly necessary. The only reason for testing is to develop an operational piece of equipment and unless we find out early in developmental progress where the areas of weakness are the equipment will never function properly as a system. In guided missile test work, it is necessary that any component failure detected in one test be determined immediately so that it may be corrected prior to subsequent testing. Similarly, in the development of new types of projectiles, all flight parameters (muzzle velocity, acceleration, attitude (yaw), striking velocity, etc.) must be determined if we are to properly understand its functioning and therefore intelligently improve its performance. The more information available the better so long as the scientific value is commensurate with cost of equipment required to gather these data.

Instrumentation techniques fall into two very broad and general categories, onboard or outside the vehicle. For equipment of sufficient size it is possible to instrument component functioning and overall performance by internal sensing devices, the readings of which may either be transmitted by radio to an outside receiver or recorded directly on some recording instruction carried internally for post test recovery and playback. For test objects of insufficient size or whose performance environment makes internal instrumentation difficult or impossible, external measurements must be made, using optical or electronic techniques.

The purpose of all instrumentation is to gather quantitative and qualitative data. Mere observation may provide data, even adequate and useful data. Generally, however, instrumentation is intended to provide measurements, that is actual numerical values for critical performance parameters. To make these measurements significant and accurate is often a complicated and difficult problem of data processing. The data recorded by the instrumentation systems are not often in immediately useable form. Data are recorded on motion picture film, magnetic tapes, hand-written logs, oscillograph paper, or even in the memory of human observers. Recorded data in such preliminary forms are called raw data. The process of translating such raw data into a numerically correct and analytically useful form is called data reduction. The result of and purpose of data reduction is the production of final data. Final data are those from which all predictable errors have been removed and from which all possible unknown errors have been corrected by statistical methods, and which are then presented in a form suitable for analysis by the test engineers.

This discussion will be primarily restricted to instrumentation techniques used in interior ballistics and exterior ballistics, therefore will be only a very limited treatment of a vastly important subject, as can be realized when the necessary instrumentation in the guided missile and atomic energy test programs are considered. Instrumentation techniques are needed to measure the various performance characteristics of a projectile (whether it is a bomb, rocket, bullet, or artillery shell). Measurements during the powered phase (within the gun tube or launcher, or during the motor burning time) deal with interior ballistics. Measurements made while the projectile travels to the target gather information on its exterior ballistics. Information gathered as the projectile accomplishes its terminal mission at the target is gathered for the so-called penetration ballistics. Therefore, for each of the three phases of a projectile's flight life, instrumentation for data collection must be provided if the ordnance item is to be proved or improved.

Increasingly finer instruments have helped considerably in ballistic research. The LeDuc

equations as presented before have been checked and corrected to a fair degree of accuracy by better instruments. In the testing of new ammunition or powder, or in the development of new weapons, it is necessary to know velocities and pressures under firing conditions. As an example, in determining a powder charge for a heavier than standard projectile to be fired in a particular gun at the same muzzle velocity as the standard projectile, it is necessary to know how the pressure varies within the bore due to the necessary increase in charge. Successive increases in charge are made and their pressure-travel curves taken using one of several types of pressure gauges. From these curves can be determined the proper charge and the proper granulation to be used.

Measurement of a phenomenon requires first that a device be utilized to convert this phenomenon into one for which measuring equipment exists. Electrical voltages and currents can be measured with great precision and expediency; therefore, a multitude of devices such as recorders and gauges have been developed which convert various physical phenomena into electrical impulses. The choice of device to make the measurements desired depends upon the physical quantity involved, its operating environment, the engineering objective, the accuracy desired, the frequency of measurement desired, reliability, funds available, equipment available, data processing facilities, time available, and many other factors. The consideration of these factors in the selection of appropriate physical apparatus, accepting a reasonable compromise according to economics and the measurement objective, is the science and art of instrumentation.

Briefly then, instrumentation requires a device to detect the phenomenon being measured and then a device to record it for detailed analysis and compilation of useful data.

A-2 TELEMETRY

The most important and most widely used type of internal instrumentation is telemetry. The field of telemetry concerns itself with measuring various parameters during flight or operation and displaying the data at a ground or other remote station. The link between the missile and the receiving station may be either radio or wire, but with the present emphasis on guided missiles, the most frequently employed telemetry system uses a radio link. In order to accomplish telemetering the following system operations are required:

(a) Pick-up or detection of the physical quantity desired to be measured.

(b) Conversion of this to an electrical analog, usually a proportional value of a standard measuring voltage.

(c) Continuous or sequential sampling (commutation) of the electrical analog.

(d) Introduction of the electrical analog to modulate a series of subcarrier oscillators.

(e) Composition of the modulated subcarriers into or onto a main radio frequency carrier which is transmitted into space by suitable antennas (or wire link transmission).

(f) Remote or ground receivers to accept the signal.

(g) Recording equipment.

(h) Demodulators and decommutators.

(i) Data display equipment (See Figure A-1).

Such a system of instrumentation is of great value since test data are available for analysis and evaluation after the flight or test has terminated; therefore, the cause or reasons for success or failure can be determined. Another area of value is found in the fact that data may also be presented on the ground in real time or at almost the same time that the parameter is being measured in the missile. This latter feature may enable engineers to make corrections while the flight or test is actually being conducted.

A study of information theory is beyond the scope of this text but it is of interest to note that in current telemetry systems it is possible to send measurements of over one hundred different parameters over a single radio link between the missile and a ground station. (Data concerning the following types of parameters are common for a telemetry system: altitude, air speed, structural strains, flutter, pressure, temperature, combustion chamber pressure, propellant flow rates, skin temperature, etc.)

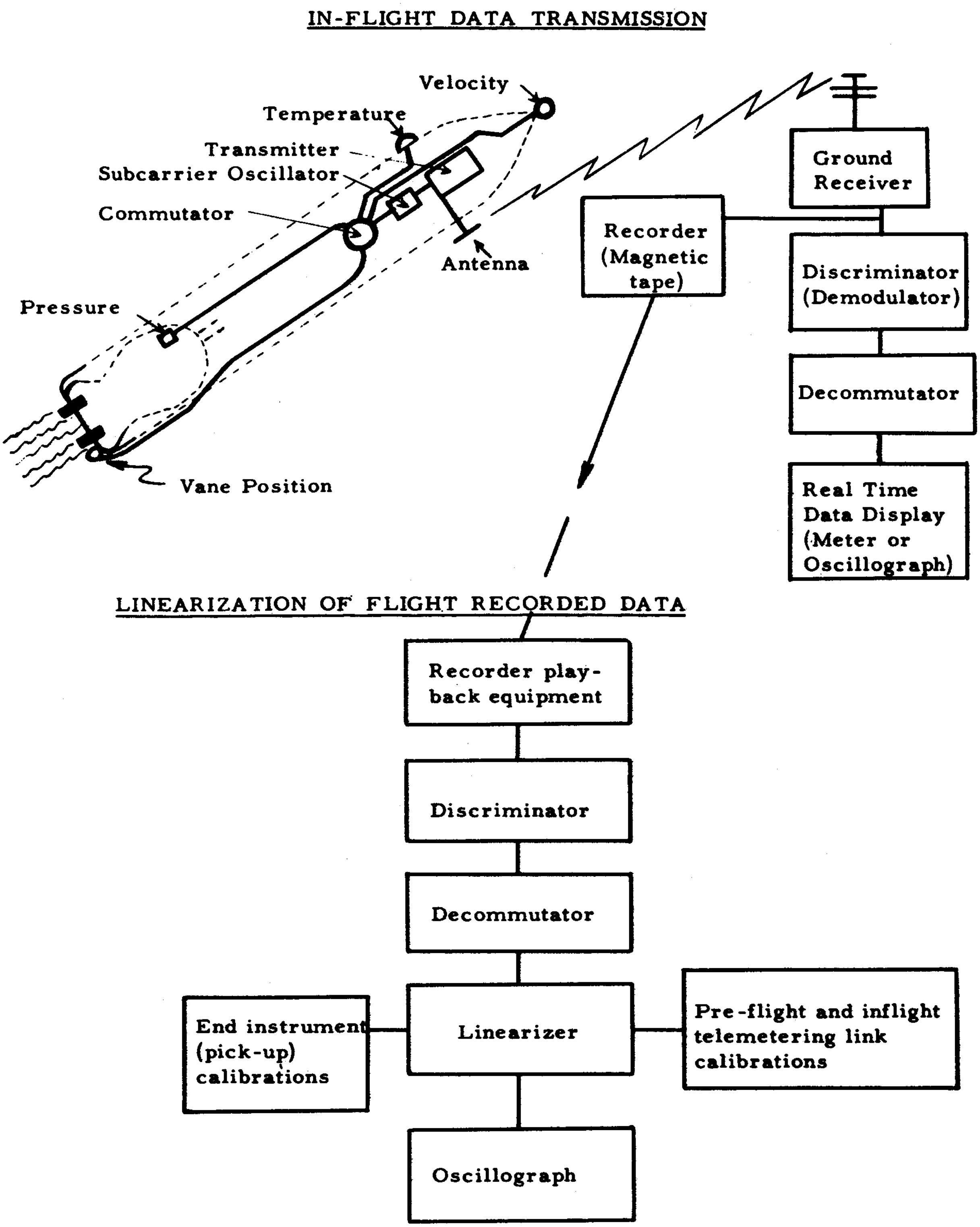

Fig. A-1 Schematic telemetering system.

A-3 VELOCITY MEASUREMENTS

There are many times when it is necessary to determine the velocity of a projectile leaving a weapon. As an example, in calibrating guns it is necessary to determine loss in muzzle velocity due to erosion so that range corrections can be applied to the sight setting for that gun. The velocity of a projectile in flight can be computed readily from the measurement of the time required for the projectile to pass between two selected points, and corrected to muzzle velocity. These two points are located approximately 70 feet forward of the muzzle since:

(a) There is continued linear acceleration of the projectile for a short distance after it leaves the muzzle due to the velocity and pressure of the powder gases emerging from the bore.

(b) The effect of the muzzle blast is felt a considerable distance from the muzzle, especially in the larger weapons. This blast is sufficiently severe to damage equipment.

There are a number of devices currently used to detect a projectile passing through known points. Some of the most important are:

Solenoid coils (Figure A-2) consist of an octagonal wooden frame with a number of turns of wire wound around the outer circumference. For a solenoid coil to be effective, it is required that the projectiles be made of a magnetic material and that they be magnetized prior to firing. The passage of the magnetized projectile through the coil induces an electrical impulse in the coil. This impulse, or signal, is transmitted to, and operates a chronograph.

Photoelectric screens are so designed that the passage of a projectile over the screen alters the amount of light falling upon it, and thus produces an electrical signal or impulse which operates a chronograph. There are several types of photoelectric screens which must be fitted to the firing range and firing conditions.

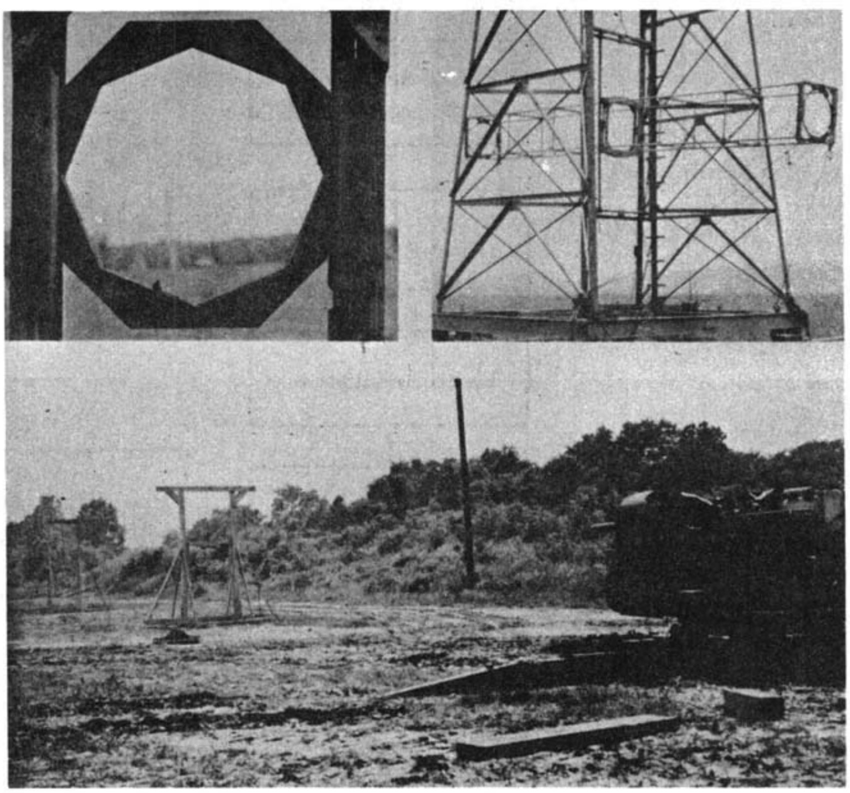

Fig. A-2 Pick-up coils for counter chronograph.

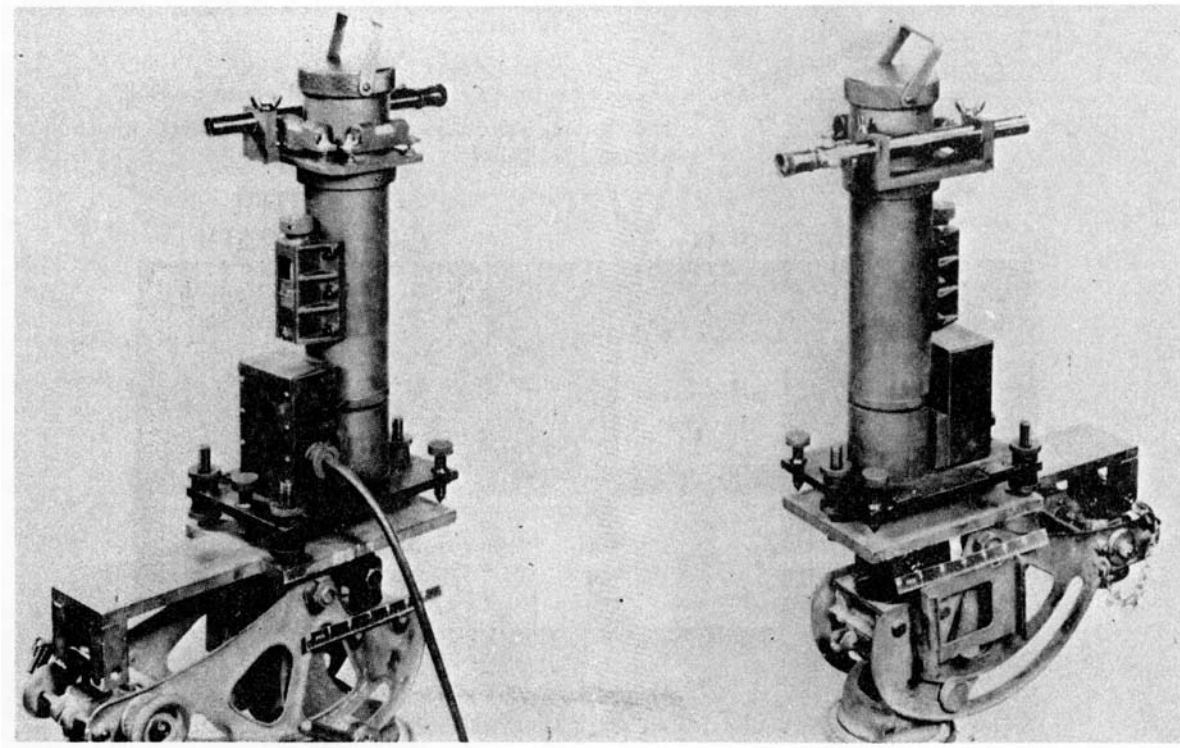

Fig. A-3 Views of sky screen showing aligning telescope and mount.

(a) Sky screens (Figure A-3) are photoelectric screens which utilize natural light. Two types of sky screens have been developed. A wide angle sky screen, requiring the projectile to pass not more than 10 feet above the screen (this 10-foot figure is subject to wide variance, depending upon the amount of illumination, the size of the projectile, and the amount of shock present due to firing the gun), and a telephoto screen, also utilizing natural light, used on high angle firings.

(b) Lumiline screens (Figure A-4) consist of an artificial source directed upon a photoelectric cell. The photoelectric cell is sensitive to abrupt changes in light intensity and it sends out a signal when part of its light is interrupted. The projectile passes between the photoelectric cell and the light source and a signal is then sent out to a recording instrument such as a counter chronograph. These screens are used principally in indoor ranges.

(c) Contact screens are a class of screens which depend upon the actual presence of the projectile to alter its physical characteristics. Boulenge screens consist of wire interlaced on a wooden frame in such a manner that the passage of a round through the screen severs the wire. Aberdeen screens (Figure A-5) consist of two layers of metallic foil separated by an insulating material. The passage of the projectile through the screen completes an electrical circuit.

A-4 TIME RECORDING DEVICES

As previously stated, velocity in itself is not measured directly but indirectly by measuring the time required for the projectile to pass between two points. The devices used to measure time are in effect very accurate stop watches called chronographs. Several types are in use.

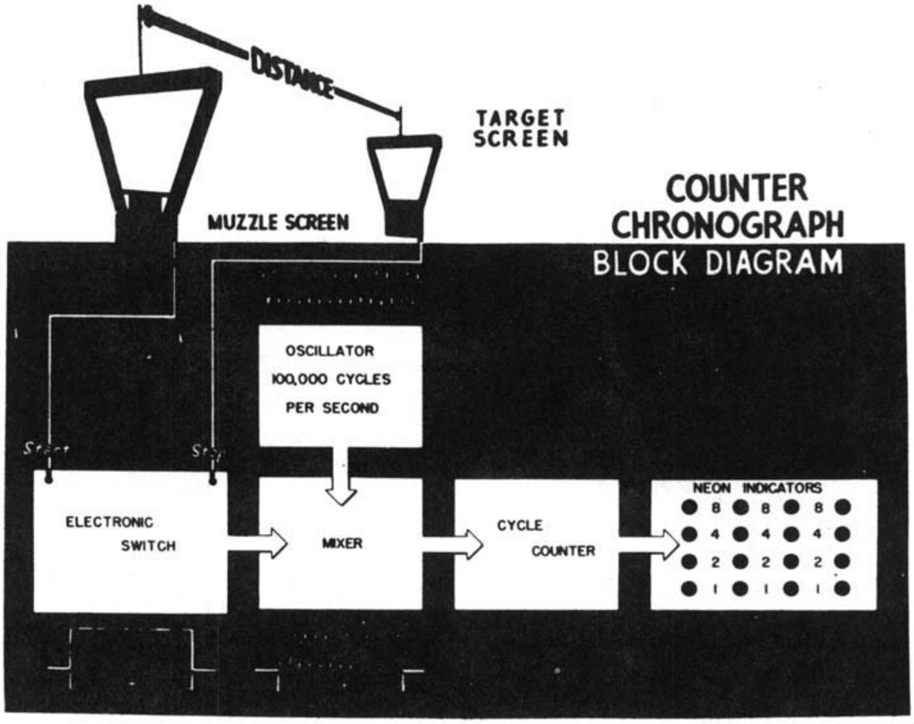

Fig. A-4 Schematic diagram of lumiline screens and counter chronograph.

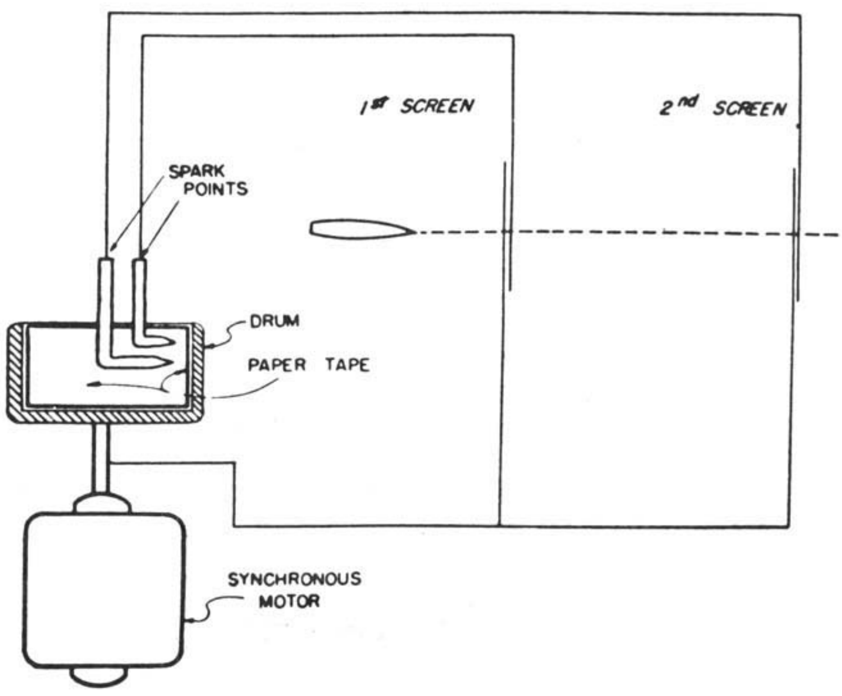

Fig. A-5 Schematic diagram of Aberdeen Chronograph.

A-4.1 ABERDEEN CHRONOGRAPH

This chronograph (Figure A-5) has been used chiefly for measuring velocities in small arms tests. The present Mk. V Aberdeen Chronograph is a portable instrument, housed in a box approximately 11 by 15 inches. On the top of the box is mounted a shallow cylindrical drum with its axis vertical, which is driven at a constant speed by a small synchronous motor. A strip of treated paper is held in place on the inner circumference of the drum by centrifugal force. This strip is punctured by a spark when the projectile passes through the screen. The time corresponding to any two spark points on the paper may be obtained by measuring the distance between the points and substituting in the equation, $t = \frac{D}{15{,}000}$, where t is the time in seconds and D is the distance measured in millimeters in the direction of rotation.

The advantages are the speed with which the results can be obtained, the simplicity of operation of the instrument, and the ruggedness of the equipment. The disadvantages are that the spark has a tendency to wander, i.e., does not always jump in a straight line; its accuracy depends upon the frequency of the power source; and the replacement of the screens must be handled with great care because of potential differences of nearly 200 volts between the foil surfaces.

With three chronographs set up in parallel and with proper adjustment of spark points, etc., the probable error of the system is about 4×10^{-5} seconds.

The counter chronograph is the electrical equivalent of the mechanical stop watch. The instrument consists of a series of counting circuits which are capable of recording time to 1×10^{-5} seconds.

Protective circuits have been incorporated in the counter chronograph to protect against false operation when random interference is present on the signal lines. Under certain conditions, such as high velocity small arms firing, protective circuits may not be sufficient to preclude the possibility of false operation. In such cases, an auxiliary chronograph should be used to check the counter.

The probable error of the counter chronograph under favorable conditions is 2×10^{-5} seconds. It is replacing the Aberdeen Chronograph.

A-4.2 CAMERA CHRONOGRAPH (SOLENOID)

This instrument is a photographic oscillograph providing a permanent record of the time of passage of the projectile through the screens or coils. Photographed timing lines permit accurate interpolation and the probable error can be maintained as low as 0.00001 second.

Measuring velocities with the camera chronograph is necessarily slow, due to the time required to develop, fix, and dry the film before it can be read. The average time for this process is approximately twenty minutes. If several firings are recorded on any one film, measurement of the first velocity may be delayed.

The outstanding advantages of the camera chronograph are that it may be used to obtain velocities over long, noisy lines; that more than two coils or screens may be used to obtain form factors and drag functions; that a permanent record is obtained which can be rechecked if desired; and that the rate of fire can be determined because of the continuously recorded operation.

A-4.3 MACHINE GUN CHRONOGRAPH

This instrument is essentially an automatic counter chronograph which permits recording time intervals of automatic cannon and machine gun fire. Readings are recorded on electrosensitive papers, thus providing a permanent record.

The instrument operates in precisely the same manner as the counter chronograph except that it can record the times, reset itself, and be ready for the next round at rates above 1800 rounds per minute.

In addition to recording velocities of each round fired, the instrument records rate of fire.

A-5 FIELD CHRONOGRAPH

This is a radar type based on the Doppler effect. A wave of known frequency is transmitted by means of a parabolic reflector behind the gun and is picked up by a receiver after being reflected from the moving projectile. The reflected wave has a slightly lower frequency than the

transmitted wave because of the Doppler effect produced by the projectile's motion. The two waves are combined by a mixing circuit thereby producing beats. These beats are counted electronically over a predetermined time interval and a velocity of the projectile computed therefrom. Advantages of this type are that it does not require the setting up of apparatus in front of the gun and therefore is not limited by terrain features; it can accommodate firings at high altitudes; and there is no dependence on light. It is very mobile, being built into two units weighing 200 lb and 75 lb, respectively. This type lends itself admirably for rendering service when and where required by artillery units.

A-6 PRESSURE MEASUREMENTS

Just as in velocity measurement, the measurement of pressure is taken with one device and recorded with another. In general the measuring device is in the form of a gauge whose response is converted to electrical impulses and measured. It might be required to find the pressure existing at any point along the gun tube, or the thrust developed by a rocket motor. Several important types of gauges are described and shown.

A-6.1 CRUSHER GAUGES

The crusher gauge (Figure A-6) operates on the principle that a certain pressure will cause a corresponding amount of permanent compression in a copper cylinder. (These cylinders are machined to exact dimensions from stock of uniform physical characteristics. Samples from each lot are then subjected to various known pressures in a testing machine, and the resulting distortion is tabulated.) A crusher gauge containing one of these cylinders can be used in several ways to test a weapon: for artillery pieces, it can be placed in the chamber or screwed to the inner face of the breechblock; for small arms, it is mounted on the side of a special test barrel. When the weapon is fired, the resulting pressure acts on a movable piston within the gauge. This, in turn, transmits a corresponding pressure to the copper cylinder, causing a permanent distortion in the metal. The amount of this distortion, when compared to the table of distortion previously mentioned, gives an indication of the peak pressure within the chamber of the weapon. Because the pressure in a gun is applied only momentarily, the reading obtained tends to be somewhat low. By multiplying crusher values for peak pressure by a suitable factor, usually about 1.2, correction is made for this error.

A-6.2 PIEZOELECTRIC PRESSURE GAUGES

These gauges consist of a quartz crystal pile acted upon by a piston. Pressure against the face of the piston acts to compress the pile, and the piezoelectric effect produces an electrostatic charge directly proportional to the pressure. This gauge is generally screwed directly into the forward face of the breechblock of a gun and

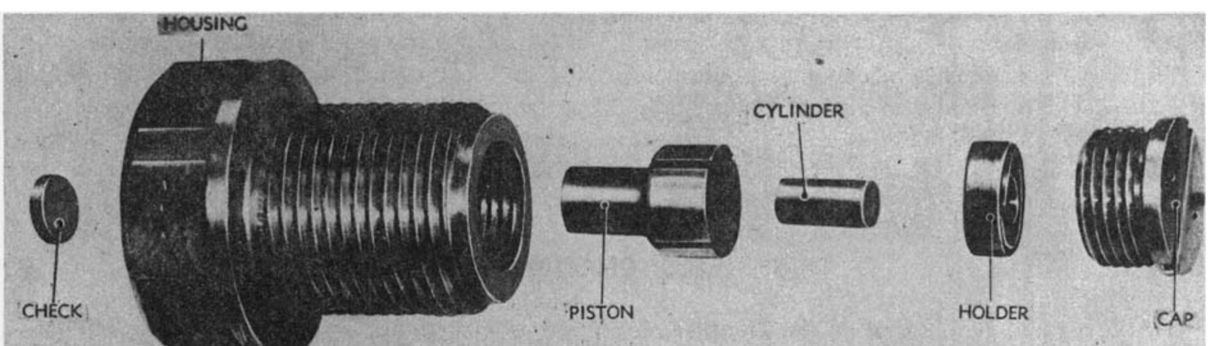

Fig. A-6 Exploded view of a crusher gauge.

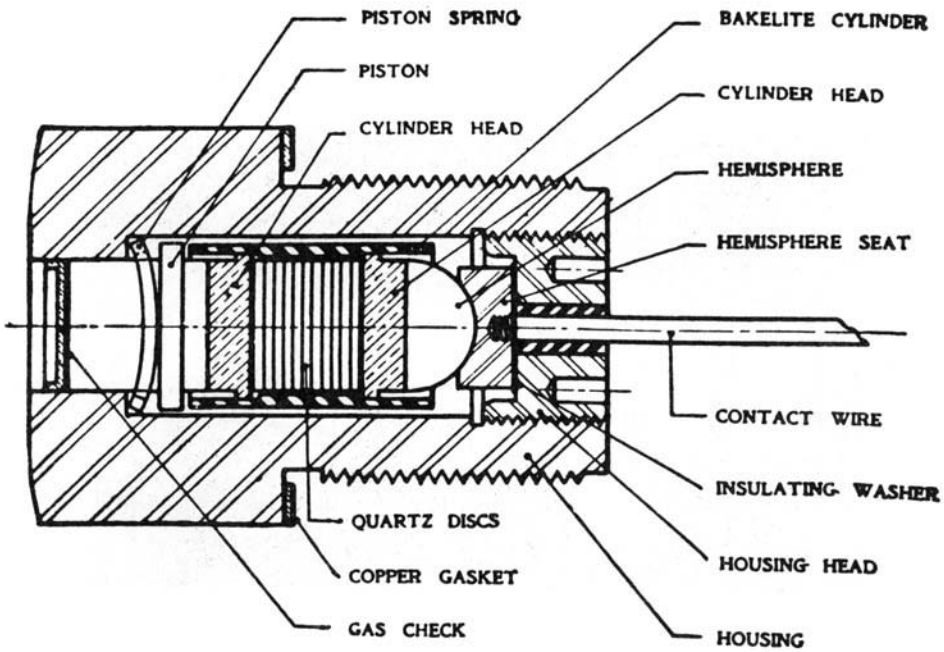

Fig. A-7 Piezoelectric pressure gauge.

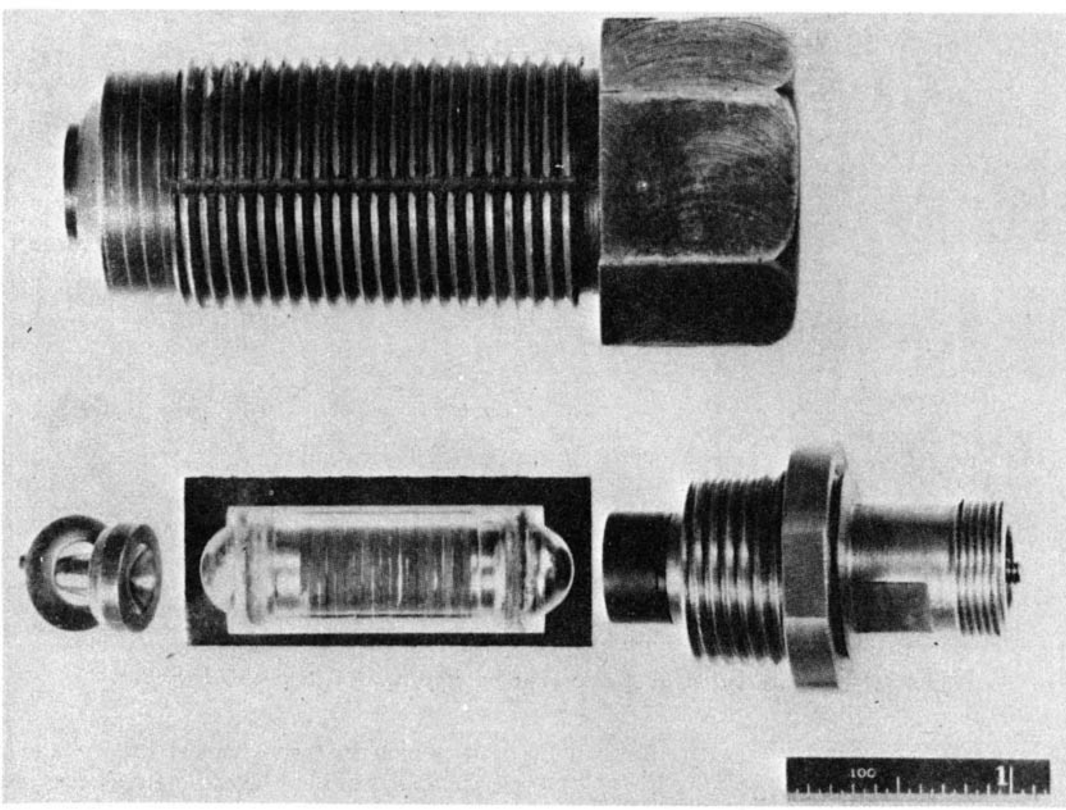

Fig. A-8 Piezoelectric pressure gauge for measuring pressures up to 80,000 psi.

connected with electrical recording instruments. Figure A-7 shows schematically the construction of this type gauge. Figure A-8 shows an actual gauge disassembled.

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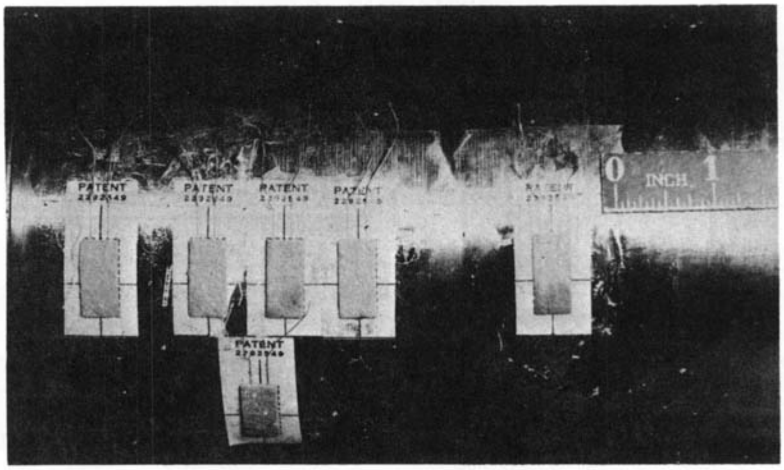

Fig. A-9 Mounting of resistance strain gauges on a gun tube.

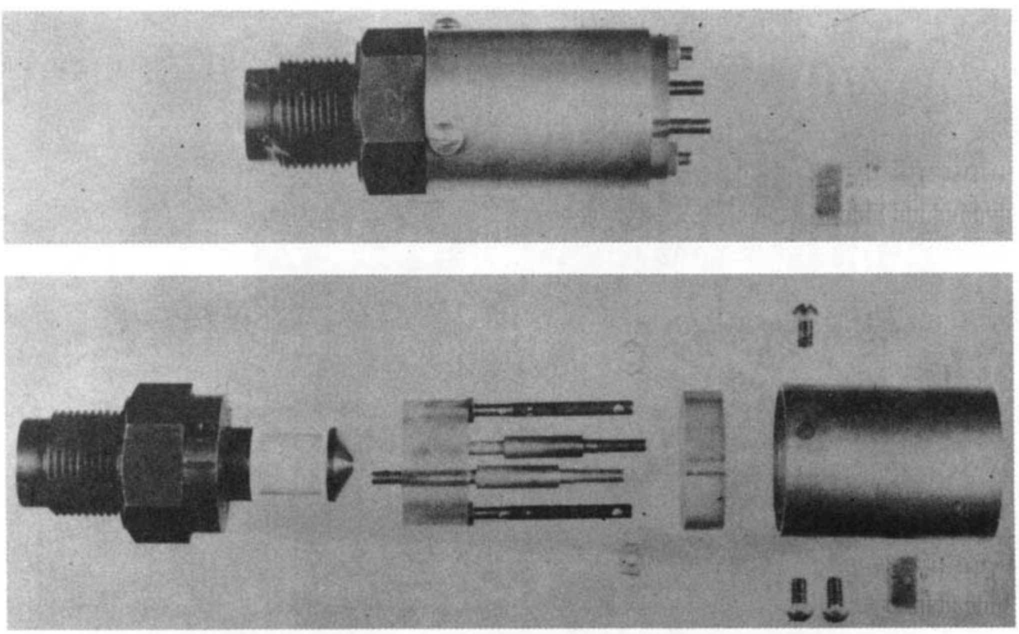

Fig. A-10 Pressure strain gauge, assembled (top) and disassembled (bottom).

A-6.3 STRAIN GAUGES

These gauges consist of a fine wire applied to a surface in such a manner that the physical phenomenon to be measured lengthens or shortens the wire. This change in length and cross section changes the electrical resistance of the wire which in turn changes the voltage in the associated circuit. These gauges are used to measure stress, strain, thrust, shear, pressure, and numerous other like phenomena. Figure A-9 shows a number of the actual gauges in place on the outside of a gun tube. Figure A-10 shows a strain gauge designed to measure pressure.

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